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THE ELECTRIC VEHICLE ALTERNATIVE

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LSSR 35-81

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This thesis discusses three basic concepts of economic analysis: the time value of money, life cycle cost, and reliability theory. Using these concepts, a method of economic analysis is developed to be used in evaluating the possible replacement of internal combustion engine (ICE) vehicles with electric vehicles (EVs). This methodology is then demonstrated by comparing two possible alternatives for replacement of the existing fleet of pickup trucks assigned to the 4950th Test Wing Aircraft Maintenance Complex at Wright-Patterson AFB, Ohio. One alternative is to replace the existing pickup fleet with new ICE pickups, the other is to replace the existing fleet with EVs. In this research effort the ICE pickup fleet is found to be the low cost alternative. Recommendations for further research and additional considerations are provided to the reader. This thesis contains an extensive bibliography on EV technology and principles of economic analysis.

LSSR 35-81

THE ELECTRIC VEHICLE ALTERNATIVE

A Thesis

Presented to the Faculty of the School of Systems and Logistics

of the Air Force Institute of Technology

Air University

In Partial Fulfillment of the Requirement for the

Degree of Master of Science in Logistics Management

By

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June 1981

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has been accepted by the undersigned on behalf of the faculty of the School of Systems and Logistics in partial fulfillment of the requirements for the degree of

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Richard T. Taheferro

COMMITTEE CHAIRMAN

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CHAPTER 1

INTRODUCTION

History of Electric Vehicles

The cost of operating motor vehicles has been increasing since the Arab Oil Embargo in 1973. As a result, the cost of gasoline has risen noticeably. For example, the U.S. Air Force was paying $.55 a gallon for regular gasoline at Mather AFB, California in May of 1977. The price for a gallon of regular gasoline at that installation rose to $1.30 in May of 1980 for a 127.5 percent increase in price in three years (48:1). During this period the consumer price index rose 64.3 percent from 180.6 in May of 1977 to 244.9 in May of 1980 (60:1; 61:1). By May of 1980, the cost of operating and maintaining standard U.S. Air Force pickups (Management Code B204) at Mather AFB rose to $.44 per mile (48:1). Other vehicles, such as flight line expeditor metros, are even more expensive to operate because their engines are not designed for the long hours of idling and slow driving typical of the flight line environment. Increasing fuel prices have spurred renewed development of electric vehicle (EV) technology which is increasing the feasibility of using EVs as replacements for internal combustion engine (ICE) vehicles.

A primary factor hampering wider use of EVs has been the heavy weight of lead-acid batteries as well as their lack of power and endurance. Nevertheless, a good deal of research and development of power sources is underway and may come up with viable alternative power sources for internal combustion engines. U.S. Air Force managers need to monitor these developments and be ready to use EVs if it will reduce transportation service costs.

EV technology is not new; it has just been largely overlooked. The first EVs were designed at the time of the commercialization of Gustave Plante's lead accumulator in 1880 (20:1). The Belgian, M. Jenatzy, set a world speed record of 105 kilometers (65 miles) per hour in an EV in 1899. Americans were also interested in EV technology during this time period.

> Nearly a century ago William Morrison of Des Moines, Iowa, exhibited an electric vehicle he had developed - what many consider the first U.S. electric car. That was in 1892 in Chicago. Between then and now electric road transportation has come and gone - literally. By 1900 38 percent of the 8,000 automobiles in America were electrics. The vehicles could not compete with the speed and range capabilities of gasoline-powered cars, however, so as this latter type of car developed electrics largely disappeared [9:2].

Though ICE vehicles also came to dominate vehicular transportation in Europe, EVs found a comfortable niche in the transportation mix in both France and England. Electric garbage trucks have been collecting garbage in Paris since 1926. Future prospects for wider use of these EVs are

bright because of their favorable operation costs, their extreme reliability and their relatively quiet operation.

Most private fleet use of EVs in the world has been in the United Kingdom where small firms, mostly dairies are using electric delivery vans.

> Small electric delivery trucks, more commonly known as milk floats, have been employed in the British dairy industry for well over 40 years. The EV fleets in this industry constitute the only long-term cost-effective large-scale EV usage in the world. There are presently three major manufacturers collectively building about 1200 to 1500 electric milk delivery trucks each year. Such a purpose-designed vehicle, built to perform a specific job requiring only limited range, many stops and starts, moderate speed, and good dependability has proven itself to be an appropriate and successful application of existing electric vehicle technology [55: p. xix].

Obviously, increasing fuel costs are the primary reason for recent, heightened interest in EVs, and further petroleum price increases will cause greater user application of EV technology. John Wigman's research of major fleet operators indicates, ". . .that from 10 to 35 percent of their present fleets could be replaced if EV ranges equal or exceed 129 kilometers (80 miles) [58:3]." There are an estimated 100 million cars and light trucks in America today. Anthony N. Ewing, Chief of the Department of Energy (DOE) Electric and Hybrid Vehicle (E&HV) Demonstration and Incentives Branch, recently stated that ". . .if 60 of every 10,000 ICE vehicles were replaced by electrics the potential electric vehicle market today can

be projected at 600,000 [56:7]." Other sources are more pessimistic. Predicasts, Inc., a business information and market research firm, predicts that user demand for EVs will reach 100,000 by 1990 and 900,000 units annually by 1995. Improved battery technology, resulting from present research and development efforts, will be instrumental in this market expansion (40:p. E-17).

EV Potential in the U.S. Air Force

The potential for EV application in the Air Force is substantial. Most transportation routes are 48.3 kilometers (30.0 miles) per day or less, at speeds of 40.2 kilometers (25.0 miles) per hour or less. These requirements are typical of present EV capabilities.

EVs are less versatile than their ICE counterparts because they depend upon electric current for battery recharging, a process which normally requires 7 to 10 hours. Users must also be careful not to become stranded because they have driven too far from an electric power source. Electric power is frequently unavailable under combat or remote area conditions. Consequently, EVs are not suitable for units stationed overseas or units which have mobility requirements. Within the United States, a manager would want to avoid excessive dependence on EVs to ameliorate the consequences of power blackouts.

The Air Training Command, the U.S. Air Force Logistics Command and the U.S. Air Force Systems Command all would appear to have operational environments amenable to EV application. The Strategic Air Command and the Military Airlift Command could also use EVs without impairing mission capability if one carefully chose their niche in the command transportation system. Security police, supply, transportation, civil engineering and aircraft maintenance personnel could all use EVs for transportation. Quick battery pack exchange capability could provide EVs with the range and endurance needed for virtually all transportation requirements.

Justification for Research

A good deal of research and development is underway in the United States and other countries to find suitable replacements for ICE vehicles. EVs are presently capable of replacing ICE vehicles in some applications but their cost effectiveness is questionable. (The authors' definition of cost effectiveness is that the cost of providing a good or service is less than or equal to the benefits which result therefrom.) The earliest EV users had little data upon which to judge EV cost effectiveness. Potential fleet users today can draw upon the experiences of the first users, but EV technology is evolving so rapidly that this data may not be valid for present generation EV components.

Sufficient data does exist however, for potential users to quantitatively estimate the life cycle cost of many EVs which are available. Even though some information is available, most current purchasers of EVs use a simple purchase price comparison of the alternatives instead of an economic analysis.

Problem Statement

The increasing cost of operating ICE vehicles, relative to the consumer price index (48:1; 60:1; 61:1), has caused the Air Force to evaluate the cost effectiveness of EVs. Final decisions to purchase EVs should be based upon an economic analysis of an EV fleet compared to an equivalent ICE fleet. Economic analysis principles need to be better applied in analyzing the EV alternative.

Scope

There are numerous types of EVs and equally many applications for them in the U.S. Air Force. There are also many methods for applying economic analysis principles when comparing alternatives. This thesis developed a method of economic analysis well suited to compare ICE vehicles with EVs. This method was demonstrated by evaluating the possibility of satisfying the flight line vehicle requirements of a maintenance organization with EVs instead of ICE vehicles. The authors compared the cost effectiveness of the American Motors General DJ-5E Electruck with

the standard Air Force pickup in satisfying the flight line vehicle requirements of the 4950th Test Wing, Wright-Patterson AFB, Ohio.

Objectives

The research objective was to develop and demonstrate a method of economic analysis for use by a decision maker in evaluating the possible replacement of ICE vehicles with EVs. Two specific objectives were pursued in development and application of the economic analysis method:

1. Use of life cycle cost, reliability, and present value concepts in economic analysis methodology development.
2. Application of the methodology in an illustrative economic analysis between a fleet of 15 standard Air Force pickups and a fleet of suitable EVs large enough to fulfill the same operational requirement as the standard pickups.

Research Questions

Six research questions served as guides to achieving the specific objectives:

1. How many EVs are required to replace a fleet of 15 standard pickups?
2. What is the present purchase price of an EV fleet and a standard pickup fleet?

3. What are the yearly operating and maintenance costs for each of the vehicle fleets?
4. Can reliability theory be applied to the analysis to aid in the determination of EV maintenance costs?
5. What is the present value of the future operating and maintenance costs, and the future salvage revenues associated with the vehicle fleet?
6. What is the life cycle cost associated with each vehicle fleet?

Answers to the research questions formed the basis for the economic analysis.

CHAPTER 2

LITERATURE AND TECHNOLOGY REVIEW

Market demand for EVs to service short distance routes exists. The authors viewed EV commercialization from macroeconomic, manufacturer, and user perspectives to gain insight into EV application potential. Past Air Force Evaluations and present efforts to reduce transportation costs with EVs were reviewed. Research and development efforts to improve batteries and other electrical components were reviewed because technical problems have limited wider, cost effective use of EVs.

Macroeconomic Perspective

William Hamilton's recent book, Electric Automobiles - Energy, Environment, and Economic Prospects for the Future,

> . . .is perhaps the most comprehensive analysis of the environmental, economic, and social constraints controlling the potential role that EVs may play in the future transportation picture of the United States. . . . The comprehensive approach to modeling EV cycle costs, energy use, utility impacts, market penetration and environmental impacts certainly reflects the major effort of a large group. . . . While most of the detailed analysis of future transportation requirements and energy/fuel availability are specific for the United States market, many of the results could be easily interpreted or adjusted for other advanced industrial nations. . . . Projections to the year 2000 of the major trends that will determine EV impact are made in comparison to

> reasonable projections of gasoline-vehicle performance. Thus, projected improvements in gasoline-vehicle fuel economy and emission levels would lessen the impact of EVs considerably in these important areas. The major conclusions of this book are presented in terms of (1) primarily economic grounds, and (2) "Societal" considerations. Thus, an individual "free market" decision based on capital and operating costs and vehicle performance will limit the market penetration considerably in the near term considered in this book. It will only be with some market adjustment through legislated approaches that the market for EVs will be enhanced to the point of having significant impact [32:18].

Hamilton covers all aspects of EV commercialization including separate chapters on future battery technology, future EV configurations and performance, EV operating conveniences and costs (market), energy-use impact, petroleum use, urban air quality, urban noise, material availability, and industrial economic impact (32:18). Hamilton shows insight into two aspects of EV technology which few EV advocates have fully considered. He believes that electricity may increase significantly in price, eliminating cheap off-peak power as a recharging source. He also cautions that raw materials chosen to manufacture batteries of the future could relieve OPEC cartel pressure only to substitute metals dependence for oil dependence (32:19). Rate structures and raw materials availability are beyond the scope of this thesis but are important aspects of the macroeconomy which will have long-term impact on the success of EV commercialization.

R.H. Carr and R.L. Curtis studied the life cycle costs of future passenger cars in 1978. Even though they assumed maintenance costs for EVs to be only 38 percent of those for ICE vehicles (8:19), inadequate battery performance (actual and forecasted) caused higher life cycle costs for most applications. Though the authors developed useful parametric cost models, they did not do a sensitivity analysis of the life cycle cost implications of increasing petroleum prices. For the purpose of their study, gasoline cost only $.134 per liter ($.507 per gallon), excluding federal and state taxes. They summarized that, "Future changes in assumed costs, particularly in the battery and petroleum costs, could appreciably reduce the electric car's life cycle cost relative to the ICE [8:55]."

Manufacturers

Jeffrey Christian's World Guide to Battery Powered Road Transportation offers the reader extensive information on development efforts underway in Australia, Canada, France, the United Kingdom, India, Italy, Japan, the Netherlands, Spain, Sweden, Switzerland, Taiwan, the United States and West Germany. Of these foreign sources, the authors find information from the United Kingdom, courtesy of D.C. Gower of Lucas Batteries, Limited, most informative. Perhaps the most fundamental question facing the EV manufacturer is whether it is best to market a purpose-designed

EV or to convert a commercially available vehicle. Lucas recognized early in its EV development program that to obtain the greatest useful work from the energy stored in the battery it would be necessary to design vehicles specifically for electric drive (24:3). The reason for this is that lead-acid batteries are so heavy that carrying the weight of the battery pack limits range of EVs (25:7). EVs which use light-weight materials can reduce vehicle weight and therefore increase range and acceleration characteristics. However, attempts by Lucas of the United Kingdom and El-bilen of Norway to market purpose-designed electric delivery trucks in the early 1970s, ended in failure because demand was not sufficient to ammortize the increased development costs which prupose designed vehicles entail.

As a result of its experiences, Lucas focused on development of EV conversions.

> When considering the advantages of purpose designed electric vehicles over those built by adapting vehicles designed for ICE propulsion it is necessary to balance the operational capabilities and operating costs of highly efficient high-cost purpose-built vehicles with the alternative of less efficient but lower cost vehicles. A detailed specific study of this question using the taxis and possible derivatives as a basis led Lucas to the conclusion that the balance of advantage was clearly in favor of the lower cost vehicles [24:3].

One outstanding feature of Lucas systems is their provision for rapid battery exchange. This feature is extremely important for EVs which must be continuously operated. Lucas has a centralized repair facility in West London to support

its EV development program. Lucas troubleshoots and repairs electric components which are beyond the capability of the fleet operators to repair (6:3). This enables the users to minimize their repair parts inventories and level of repair expertise needed.

In other countries, companies such as Fiat, Toyo Kogyo and Suzuki all have aggressive plans to market EVs commercially in the early 1980s. They are also aiming at fleet sales of commercial vehicles rather than concentrating on passenger vehicles (9:5). Their reasons for doing this are similar to Lucas's; fleet sales allow the manufacturers to develop their EVs in controlled environments where proper maintenance is likely. Close collaboration also helps the companies to engineer their EVs to meet user needs.

The United States is behind other countries in application of state-of-the-art EV technology but is putting more effort into research and development of battery, fuel cell and fly-wheel technology, as will be discussed later. On September 17, 1976, the U.S. Congress passed Public Law 94-413, which calls for expenditure of $160 million over the next five years to spur development of EV technology. While the most visible aspect of the program is to put 10,000 domestically manufactured EVs on the road by 1984, the research and development efforts stimulated by this law

in battery, fuel cell and flywheel technology may greatly advance EV technology in the next five years (9:6; 16:92).

A survey of the manufacturing firms involved in EV production in the United States reveals a wide variety of firms. In contrast to countries such as West Germany, the United Kingdon, Italy, and Japan where the largest vehicle manufacturers are developing EVs, most of the EV manufacturers in the United States are small businesses, employing less than five people. Many of these small firms lack formal plans for market expansion and are starved for development capital (9:5). The big three American automobile manufacturers are developing EVs but do not have any that are commercially available at this time.

Government policy under PL 94-413 has been to assist entrepreneurs large and small, in their endeavors by providing loan guarantees for development capital, with top priority being given to commercial production of EVs (58). To date, two firms, Jet Industries of Texas and Electric Vehicle Associates of Ohio have been awarded loan guarantees of $3 million each (15:2).

The big three automobile manufacturers are taking a more cautious approach to EV development. Ford is privy to important information through its contacts with Ford of Britain. Chrysler is researching EV technology but has not built prototype EVs. General Motors Corporation has converted a fleet of 35 BEV-1 electric vans for research and

development. GMC's ". . . objective is a future production vehicle including vehicle, electrical components, and battery life (advanced technology) of 100,000 miles [47]." General Motors Corporation will enter the EV market when it has developed an EV whose capabilities will generate demand sufficient to warrant mass production.

The AM General Corporation, a division of American Motors has manufactured and delivered 352 DJ-5E Electrucks to the U.S. Postal Service (USPS). These vehicles dominate the USPS EV fleet, which is the largest (55:p. vii) and best documented in the USA. American Motors provided electric drive as a factory option which reduced cost.

Users

Overview. The authors obtained information about the experiences of American private and public sector users as well as U.S. Air Force users. Most of the EV fleet users in the United States are either government agencies or utility companies. Users usually purchase EVs from the lowest bidder on an invitation for bid. Major problems with electric components were encountered by the earliest users but problems with controllers and chargers are well on their way towards resolution in later generation components. However, all of the users have been disappointed by performance of their lead-acid batteries. These batteries need longer service lives and consistant performance

characteristics. Users are dismayed by the significantly degraded performance they are experiencing as these batteries age and are subjected to cold weather. Major improvements are needed in battery technology to increase demand for EVs.

Lead-acid battery lives are unsatisfactory given present petroleum prices. As of 1978:

> Battery life has been the user's biggest problem with electric vehicles in the United States and Canada. Of the vehicles surveyed only those involved in the USPS program have accumulated sufficient use and maintained adequate records to define battery cycle life. The USPS DJ-5E's have been experiencing a battery cycle life of about 300 cycles. . . the 300 cycles is representative of the life reported by most other users of American-built vehicles. None of those surveyed have been able to get much over 9654 kilometers (6000 miles) out of a set of batteries. At the daily average mileage of most electric vehicles this represents a cycle life of 250-300 cycles. Many users have reported much shorter battery life. However, the Harbilt vehicles offer considerable encouragement as they have all accumulated more than 16000 kilometers (10,000 miles) without any total battery replacements (a few vehicles have had one or two cells replaced) [59:84].

The authors believe that the favorable environmental and operational characteristics of the Harbilt operation at Cupertino, California strongly influence the higher battery lives achieved there. The 31 Harbilts operated in Cupertino have average postal route distances of 18.1 kilometers (11.3 miles) with none of the routes exceeding 29.0 kilometers (18.1 miles). None of the routes have gradients in excess of 5 percent and the climate in Cupertino is mild

with temperatures ranging between 7 and 38 degrees Centagrade (45 - 100 degrees Farenheit) (59:p. 4-2).

Performance of the Harbilt EVs in Cupertino, California has been the best of any EVs in the United States. Theoretically, EVs should have lower maintenance costs because they have fewer moving parts, and there is no heat or vibration stress on the power plant or chassis (41). The USPS Harlibuilts in Cupertino have a 99 percent availability rate and an operations and maintenance cost of $.085 per mile compared to $.120 per mile for ICE Jeeps (59:p. 4-4). It is the only EV type for which the data showed lower operations and maintenance cost when compared to ICE vehicles.

Private Sector Users. Between 1974 and 1978 104 Battronic Minivans were tested by 59 American utilities, one Canadian utility, and the Lead Industries Association. Test sites incorporated every sort of climate in the 48 continuous states. Between July 1975 and the summer of 1976 the vehicles could not be operated until the front axles, which were recalled by the Clark Equipment Company, could be completely replaced to correct a structural weakness problem, a problem shared with the EV Minivan's ICE counterpart (59:p. 5-7). Battery charge level gauges failed quite often, in some cases several times on the same vehicle. "Besides occurrences of not functioning at all,

the gauge also showed to be basically unreliable [59: p. 5-14]." Converters also caused problems:

> The converter failed in a few cases, more than once on the same vehicle. . . . Failures mostly involved failure to charge, but in some cases it overcharged the 12-volt battery and it dried out, so that the battery had to be replaced [59:p. 5-14].

Users also experienced controller and charger failures. However, the users themselves were able to repair most of them without difficulty. Some users constructed battery doors inside the vans so that mechanics could service batteries from inside the van without having to remove them first with a forklift. Otherwise, the users were satisfied with Battronic's quick battery change arrangement (59:p. 5-16).

The average battery life for the Battronic minivans was 200 cycles or one year (59:p. 5-27). Detailed battery performance analysis by the Omaha Public Power District, where route requirements were in the 32 to 48 kilometer (20-30 mile) per day range, in often bitter cold conditions, are of extreme interest to potential users in cold weather areas. Ranges of 40-80 kilometers (25-50 miles) per charge were typical when the batteries were new; as they became older ranges sank to 16-34 kilometers (10-21 miles) per charge. Change of EV route profiles prevented deterioration in service as the batteries matured (59:p. 5-30).

The authors interviewed several EV users, paying particular attention to battery life and component

reliability. Consolidated Edison of New York City is operating a fleet of 20 EVA pacers and 14 EVA Fairmonts in Queens. Battery life has been much less than 300 cycles. Initial battery chargers installed on the vehicles are not compatible with batteries in use; the result being that the batteries were frequently being overcharged. Vehicle range is at least 32 kilometers (20 miles) per recharging cycle, but does not exceed 48 kilometers (30 miles). Mileage is dramatically affected by cold weather (23).

The Long Island Lighting Company (LILCO) in Mineola, New York is operating a fleet of 47 vehicles located at six sites (8 EVA Pacers, 12 Jet Electra Van 600's, 1 Jet Electra Van 1000, 19 Electronics Omnis, 6 Citi-cars, and 1 Jet 1000 P Pickup). Reliability of the vehicles has not presented problems though the cold weather has drastically reduced vehicle range. EVs are normally getting 48 to 56 kilometers (30 to 35 miles) per recharging cycle; during the winter, range is dropping to approximately 32 kilometers (20 miles) per cycle. LILCO previously had quality control problems with General Electric batteries. New batteries had a burn-in mortality rate of 2 to 4 percent, a problem which was solved by buying the batteries under warranty. Only 25-50 percent of the batteries were lasting 300 cycles. Most of them had to be replaced after between 1 and 1 1/2 years of Monday thru Friday operation. LILCO is presently using Varda batteries which have filter caps

which reduce explosive hazards and allow checking of batteries in two to three month intervals instead of the former 3 week interval (34).

DC motor torque on the 12 Jet Electra Van 600's is not sufficient to permit smooth gear shifts, especially during rapid acceleration. Range of the Jet Electra Van 1000 is limited by a full payload (34).

General Telegraph and Electronics Corporation (GTE) has 189 Jet Industry 1/4 ton pickup trucks, sedans and mini vans (Tampa, Florida, 25; Long Beach, California, 25; Honolulu, Hawaii, 25; Everett, Washington, 15; Portland, Oregon, 10; Columbia, Missouri, 10; Bloomington, Illinois, 10; Marion, Ohio, 10; Erie, Pennsylvania, 10; Lexington, Kentucky, 10; Durham, North Carolina, 15; Dallas, Texas, 20; and Pomona, California, 4 (with zinc-chloride batteries)) (15:8). GTE has not been satisfied with battery performance. GTE discontinued use of earlier Exide XPV-23 batteries, and has not been satisfied with the superior performance promised by Varda on its batteries (300 to 600 cycles). The latest Excide battery presently in use seems to work well with the General Electric chargers.

> On the subject of batteries, our experience has not been as positive as with other components. Our first 75 vehicles were received with Exide XPV-23 batteries. These batteries provided exceptionally good performance early in life, however, fairly rapid and continuing degradation in range has been experienced. We are currently negotiating with Excide for replacement of these particular batteries. The XPV-23 batteries have gone through several

> modifications and the present iteration is the XPV-23-3. While it is too early to provide long-term life characteristics of this new battery, early indications are that this battery is superior to the early models [26].

Clifford L. Hayden, GTE's Director of Energy Resources, says the chargers need to be modified to prevent over and under charging of the batteries. The controllers are drawing more than the 80 percent discharge rate (27).

GTE has experienced few reliability problems:

> We have had one charger explode due to unknown causes. The explosion completely destroyed the charger but was contained in the charger housing with no external damage. We have had some printed wiring card failures associated with the controller. We have also had to change out one controller in total due to our inability to diagnose its problem [26].

Hayden recommends that the Air Force buy batteries on warranty, trying different batteries from different companies in a pilot program. The Air Force should seek a guarantee of 500 cycles and nothing less than 250 cycles should be accepted. He believes that a battery life of at least 20,000 miles is required for cost effectiveness (27). GTE has not achieved this battery life goal yet.

Gregory J. Ostrowski, Senior Market Development Manager for Detroit Edison finds battery life is the most critical component in its one 1977 EVA Pacer, especially in driving life cycle cost. He shares the following information:

1977 EVA Pacer	26 months in-service
Top Speed	65 mph
Energy Economy	1.12 miles per KWh
Electricity cost at 5¢ per KWh	4.5 per mile
Battery Life	502 cycles
Total Miles	5500
Replacement Cost	$1600

Despite the unusually high battery life achieved at Detroit Edison the vehicle has a higher life cycle cost than an ICE Pacer. Ostrowski believes that,

> in the mid 1980's when intermediate range (advanced batteries) electric passenger cars are mass-produced, they will indeed be cost effective compared to liquid hydrocarbon fuel vehicles [39].

Northrup is planning purchase of 30 EVs from South Coast Technology which will be equipped with nickel-iron batteries supplied by Eagle Pitcher (15:9). Results of this test program should be interesting because Northrup will be the only commercial user of nickel-iron batteries. Hopefully, higher performance batteries will allow the vehicles to operate two shifts, daily, before needing recharge.

Public Sector Users. The largest and most successful user of EVs in the United States is the USPS. A comprehensive report on the USPS experience is contained in DJ-5E Electruck USPS Results (55). The primary reason for the program success has been that the average daily routes of the vehicles, 8 to 16 kilometers (5 to 10 miles) per day are well within EV capability. Operating terrain is generally flat and test locations have been in relatively mild

climate areas. At present the USPS is operating 352 American Motors General, DJ-5E Electrucks and 31 British Harbilts. The DJ-5E's, were purchased through competitive bidding (59:p. 4-2). While the cost per mile for operation of EVs is slightly higher, the cost per day of operating EVs is less than for ICE vehicles because EVs are serving the shorter service routes. Therefore, the USPS intends to procure 375 EVs in FY 1981 and 1200 EVs in FY 1982 (5).

The Ohio Department of Transportation was one of the first users of EVA pacers, having purchased them in 1977. Mr. Tom Foody, EV project manager for the department, attempted a life cycle cost analysis of the vehicles which included all aspects of operating and maintenance costs. He concluded that the EV would have to be operated for approximately nine years in order to break even, dollar wise. Since there was no data base available, technological problems which have caused greater operating and maintenance costs, could not have been anticipated. The two EVA Pacers purchased experienced 12 converter failures in one year. The department experienced major difficulty in obtaining replacement parts and repair service. The DC Systems battery charger was unsatisfactory because it is difficult to properly set the charging timer. Overcharging of the batteries shortened the life of the batteries, preventing a 300 cycle life; however, batteries could easily

last 300 cycles, or one or two years, with proper charging procedures (19).

Mr. Leon Talbert, Ohio Department of Transportation Engineer summarizes:

> While the outcome of our analysis is not yet available. . .the battery will play a key role in determining the life cycle cost characteristics for the electric vehicle. Just as the battery performed the decisive role in controlling the actual field performance, it has also turned out to be the factor in our cost model that was the least accurately estimated. Our estimates of battery life were consistently high compared to the actual battery life experienced over our three years of ownership. Since the battery cost can represent up to 15 percent of the purchase price, additional battery purchases over those originally estimated clearly has a significant effect on the EV life cycle cost characteristics (50).

One interesting aspect of the program is that the Pacer with a standard transmission gets about 30 percent better mileage per charge than the Pacer with an automatic transmission. The vehicle heater sometimes emits fumes which are bothersome. Weight of the battery pack causes steering response to be sluggish. Tom Foody emphasized that compatibility of the charger and batteries is a major problem. The primary reason for this is that battery manufacturers do not manufacture chargers and vice versa (14).

The authors were also interested in determining how local governments were purchasing EVs. Reports from Dayton, Ohio, and Ft. Collins, Colorado, indicate that local government agencies usually accept the lowest EV manufacturer bid on invitations to bid. The City of Dayton, Ohio,

recently purchased two EVs after a simple price comparison between alternate suppliers. These vehicles will be evaluated by comparing operation and maintenance costs of these vehicles with similar ICE vehicles to see if any cost savings can be realized (2).

Mr. Greg Reese, Equipment Services Manager for the City of Fort Collins, offers the best explanation of some of the problems faced by the first managers who purchased EVs, given the great uncertainty which existed at that time.

> When we wrote specifications for our EV's, we were more concerned with acquiring vehicles from a reputable and proven EV manufacturer than we were with trying to purchase the most cost-effective vehicles available. . . . We did not do any life cycle costing in evaluating the specifications or the bids received because any data used for that purpose would have to have been obtained elsewhere from people operating vehicles under different circumstances, and we would not have been comparing "apples to apples", and also, this type of information was scarce and incomplete at best [44].

Mr. Reese plans to compute life cycle costs after two or three years of operations and maintenance data have been compiled. He emphasized that battery life is a major factor driving cost. The other factor he cited was the high purchase prices of EVs. Hopefully, the demonstration projects at Ft. Collins and around the country will help "EV manufacturers progress toward mass production capabilities and reduce vehicle prices as a result [44]."

U.S. Air Force EV Development Efforts

The U.S. Air Force has been following EV technological developments with interest since the late 1960's. The U.S. Air Force Logistics Command Directorate of Material Handling Equipment at Warner-Robins Air Logistics Center authorized the Air Training Command to do the first EV evaluation in 1970 at Randolph AFB, Texas. EV's used were three different golf-cart type vehicles manufactured by Cushman, Westinghouse Electric, and Electric Carrier. The three vehicles were tested over a three month period where they performed for maintenance, supply and the security police. The vehicles were found to be satisfactory for use if continuous operation and speeds in excess of 10 miles per hour were not required. Mr. F. Brumley, Chief of the ATC Headquarters Maintenance Evaluation Branch did a comprehensive evaluation of the life cycle cost of these EVs, using a 10 year period as the basis for his estimate. He found that the life cycle cost of operating the EVs was $.121 per mile versus $.126 per mile for pickups. The test also revealed that annual replacement of the batteries would be required, assuming a utilization rate of 240 days per year. During the test, utilization of the EVs averaged only 2 hours of operation per day and the vehicles had an operational range of roughly 16 miles before recharging was necessary (7:17;18). Though cost-effective to operate

under certain conditions, these EVs were not adopted for Air Force use because of their limited capability.

During this same time period, the Tactical Air Command operationally tested the same three types of EV's as well as an EV van and a twelve passenger EV bus manufactured by Battronic of Boyerstown, Pennsylvania. The project report on the Cushman, Westinghouse, and Electric Carrier EV's at Seymour-Johnson AFB, North Carolina, stressed the importance of proper recharging procedures but did not consider the impact of battery replacement on life cycle cost. Maintenance problems on these vehicles surfaced during the year long test from 9 October 1970, to 15 October 1971 which did not surface during the three month trial at Randolph AFB. The brakes locked on the Cushman Vehicle (Titan Model 30271) on 4 January 71 and failed completely ten days later. There was a battery short which destroyed the battery pack on the Westinghouse EV (Model 234). The steering mechanism broke 26 January and a repair part could not be obtained until 12 March 1971. After repair, the steering mechanism broke again on 4 June 1971. The Electric Carrier (Model 604) performed without problems, but two tires had to be replaced 8 September 1971. Despite these problems, the vehicles were recommended for use based on the most obvious and least significant factor of EV life cycle cost, electricity consumption per mile.

The Battronic vehicles were tested between 9 October 1970 and 15 August 1971 at Langley AFB, Virginia, as possible replacements for Chevrolet step vans (Management Code B216). Test of these vehicles is significant because they are equipped with a quick battery pack changing capability to allow continuous operation. During the test battery charging took longer (8 hours) than battery depletion (7 hours). As a result, quick battery removal and replacement enhanced capability but could not ensure continuous operation. The vehicles functioned well throughout the test period, with no extraordinary maintenance problems. In fact, maintenance cost per mile was less for the Battronic vehicles ($.009) than for Chevy step vans ($.042) (36). (These results conflict with those of the previously described test conducted by 61 users operating 104 Battronic mini vans at approximately 61 locations between 1979 and 1978 (59:Section 5)). The primary weakness of this evaluation is that, once again, the most obvious and least significant aspect of EV live cycle cost, electricity consumption, was emphasized while battery life was overlooked. However, procurement of the Battronic vehicles was not recommended because the higher initial purchase price, when ammortized over a ten year period using the straight-line method of depreciation, caused a higher life cycle cost when compared to that for a Chevrolet step van (33).

The Air Force currently has one major test program underway to determine the cost effectiveness of EVs. The U.S. Air Force Directorate of Logistics has made $100,000 available to the Air Training Command (ATC) for local purchase of twenty-three EVs. These vehicles are being evaluated at six ATC bases to determine their operation and maintenance costs (12:1). These vehicles are being procured from four different manufacturers, Cushman, Nordco, Taylor-Dunn, and Tram Industries. First actual delivery of an EV was at Mather AFB, California, during the last week of October, 1980 (17). The vehicles are distributed in Table 2-1 (12:1). The purpose of the evaluation is to test the EVs in as many environments as possible to determine if they can be cost-effectively integrated into the Air Force transportation mix.

The most interesting aspect of the project is that EVs purchased have lower operational capabilities which are intended to satisfy mission requirements, in cases where vehicles in use, pick-ups, busses, and an AGE tow tractor, are overpowered for the real mission requirements. The intention of the program is to blend the EVs of lower capability into the transportation mix to fill roles where their capability is good enough. If the EVs can do the work required, the possibility of cost effective operation is good because the higher purchase price of converted ICE

TABLE 2-1

AIR TRAINING COMMAND EV DEMONSTRATION PROGRAM

Air Force Base	Vehicle Type	F/L Tram	Maintenance	Supply	Civil Engineers	Security Police
Columbus AFB, Mississippi	Cushman 31F			2		
Keesler AFB, Mississippi	Taylor Dunn "8"			2		2
Laughlin AFB, Texas	Taylor Dunn "8"		2		2	
Mather AFB, California	Nordco 262C	1	4	2		
Reese AFB, Texas	Cushman 31F		2	1		
Williams AFB, Arizona	Nordco 262C	1	2			
TOTAL		2	10	7	2	2

vehicles has been avoided by purchase of the golfcart-like Cushman, Nordco, and Taylor-Dunn vehicles.

The ATC EVs will be evaluated in a two year test program. Preliminary reports from the users indicate that the vehicles have serious limitations. All of the users have complaints about driver comfort during adverse weather because the cabs do not have heaters, defrosters, and suitable windshield wipers and they leak water. Laughlin AFB, Texas, reports having had trouble tapping a 12 volt power supply for their flightline radio. Other shortcomings include lack of mirrors, bed rails, pintle hooks, and a heavy duty steel deck plate in the truck bed. The transportation squadron at Laughlin AFB, Texas will build a battery holder which will have quick battery change capabilities (35). Reese Air Force Base, Texas, reports having to curtail EV operation when winds exceed 25 mph as well as dissatisfaction with the cargo carrying space. Mather AFB, California reports that battery drain due to headlight operation during inclement weather limits service life to approximately 4.5 hours of continuous operation. Maintenance personnel report satisfaction in using EVs for specialist dispatch. Their 4 EVs are kept either indoors or under cover when not in use. Battery charging during these standing times has presented limited battery capabilities from impairing dispatch service. The Field Maintenance Squadron

spent about 38 manhours and $120 in materials constructing a rear canopy for one of the vehicles (49).

The Air Force Logistics Command has received Department of Energy funding to conduct a Management and Equipment Evaluation Program for a total of 15 Jet Industries vans and pickups which are converted ICE vehicles. The overall program manager for the EV demonstration project is the Civil Engineering Directorate of AFLC Headquarters (11:13). The vehicles are being centrally procured by the Warner Robins Air Logistics Center for use, five vehicles at each location, at Wright-Patterson ALC, Ohio, Kelly ALC, Texas, and McClellan ALC, California, by supply, civil engineering, transportation and other base functions at the discretion of local vehicle operations officers. The operation and maintenance costs of these vehicles will be analyzed to determine the cost effectiveness of replacing standard ICE vehicles with their converted EV counterparts (11:3). At present AFLC is also considering a test program to evaluate the same S&S battery powered TowTrac which is being evaluated by United Airlines. Information will be shared between the Air Force and United Air Lines (63).

EVs are not without advantages. Development of this technology to a cost effective level could have a significant impact on oil imports and consumption, while taking advantage of electricity generated at night during off-peak hours. None of the users surveyed have experienced

cost effective EV demonstration programs. The authors must agree that ". . . it is well to recognize that electric vehicle technology is still a risky investment, unless heavily subsidized, and that there is no guaranteed solution to the energy crisis just around this particular corner" (16:92).

Battery Technology

The prospective user is interested in four aspects of battery performance:

1. Adequate and consistent range
2. Adequate and consistent speed
3. Adequate life
4. Reasonable battery price.

The only battery which is presently coming close to satisfying all of these requirements is the lead-acid battery. Still, lead-acid batteries leave much to be desired. A primary problem is that battery packs ". . . are so heavy that much of the vehicle's power is used up simply carrying its power source. Vehicles powered by them require some 10 percent more energy to travel a mile than do those powered by petrol; their fuel efficiency looks even worse compared with diesel engines [16:92]." Helmut Domann and Stefan Renner identified lower battery prices and/or increased durability through an increased number of cycles as two means of reducing EV operations cost (14:25).

Researchers have been trying to improve the power density of lead-acid batteries. The only means of doing this is to reduce the proportion of battery weight due to the battery case (52:3). The West German firm of Varta has probably done as much, if not more, research and development of lead-acid batteries as any western battery firm and still has not been able to significantly improve power and range (technical) characteristics of the battery (26:3). Given that technical characteristics of the lead-acid batteries have been fully developed, one would hope that the battery life could be significantly improved. A NASA survey of EV users indicated that none of them in practice is getting much beyond 400 recharging cycles battery life, and then most of them are getting less than 300 (59:84). The authors' telephone interviews with Con Edison, Long Island Light and Power Company and General Telephone and Electronics revealed that their battery lives are 300 cycles or less.

While the Europeans and Japanese appear to be concentrating on development of existing technology, American firms such as General Motors, Westinghouse, Eagle Pitcher and Gulf and Western are researching advanced technology batteries.

> . . .Battery researchers seem to be caught in uncomfortable tradeoffs between increased battery life and increased power-storing efficiency. . . . the nickel-zinc batteries that GM plans to put in its electric vehicles enjoy good storage efficiency,

> enabling the traveler to go long distances without a recharge, but such batteries wear out quickly because the zinc they use gets dissapated in their charging/discharging cycle. GM plans to have such problems solved by 1985. . . the opposite problem-long life, low performance-plagues the nickel-iron batteries now being developed by Westinghouse and Eagle Pitcher in the USA. More complex batteries (like Gulf and Western's zinc-chloride battery or the molten-salt batteries developed by a number of researchers) could run a foul of their own complexity [16:95].

Hans Niklas and Dietrich Berndt of Germany evaluated different battery technologies and found that the higher cost of nickel/cadmium battery production, similar to the nickel/zinc batteries General Motors is researching, makes their use in future EVs unlikely, even when economies of scale are achieved (37:9).

Development of fuel cells is an even more technologically challenging task.

> . . . it would appear that with the present state of knowledge and technical development, the cost of manufacturing fuel cells remains the major obstacle blocking their development. . . . The studies, still considerable in number, which are still being carried out do however permit a gradual advance toward technical and technological mastery of these systems. They leave some hope of a favorable outcome at some future time which, nevertheless still remains distant [29:10].

The DOE recently evaluated progress of the Gulf and Western zinc-chloride fuel cell battery and concluded:

> . . . Auto industry experts are concerned with how the G & W battery controls the release of poisonous chlorine gas in the case of an accident. . . Unlike the lead-acid battery, the zinc-chloride system requires a technician in attendance during charging because the automation is not yet complete. But more importantly, the technology needs to be

> improved in the areas of compatability and energy efficiency of the components. Also cost reductions in materials and assembly techniques must be addressed before the battery can realistically be considered for commercial production levels. G & W estimates that by 1983 these refinements could be achieved [57:3].

Reports in October 1980 were that the zinc-chloride battery was suffering from fundamental technical problems.

> . . . the battery achieved less than 65 percent of its expected power output. . .freeze ups in the heat exchange part of the power pack have severely reduced its capacity to hold a charge, and. . .the battery is so difficult to service that it can be recharged only by highly trained personnel [15:1].

The authors believe that present lead-acid systems will be obsolete if any of the developing battery technologies are successful. Close scrutiny of General Telegraph and Electronics Corporation's experimental test of zinc-chloride batteries on four EVs at Pomona is advised. Likewise vehicle procurement officers should closely observe Northrup's experimental use of Eagle Pitcher nickel-iron batteries on its 30 EVs.

Other Aspects of EV Technology

There are two main types of chargers, chargers with timers and Ferrell resonant chargers which cut off automatically when the batteries are fully charged. J. Bradbury was able to show in a study that overcharging due to faulty charge time setting limits the range of EVs (6:4). Richard Ollie, Chief of Engineering of EVA highly recommends Ferrell resonant chargers to users (38).

Numerous experts have recommended development of transistorized controllers to reduce noise, heat and improve efficiency. Some of them were Gallot of France in 1975 (20), Giampiero and Brusaglino of Italy in 1976 (21), and Bradbury of the United Kingdom in 1980 (6). Development of transistorized controllers has been delayed due to difficulty in achieving transistorized control beyond 6 kilowatts. Transistors capable of functioning in this regime were too expensive for commercial development until recently. These technical problems have been solved and EVA is presently developing a transistorized controller for use in its production vehicles by 1984 (38).

A most significant finding is that the manual transmission is the most efficient transmission available at the present time (21:9). At present the USA is leading the world in research of continuously variable transmissions (CVT) for use in EVs. Preliminary studies indicate that CVTs will reduce battery power requirements due to better transmission ef.iciency and therefore allow a significant reduction in required battery weight (15:20).

The heavy load of the batteries puts greater stress on EV brakes than is the case for ICE vehicles. Development of EV brake technology has followed two lines. Companies such as Jet Industries are experimenting with alternate types of master cylinders to reduce the high pedal effort required for braking which is characteristic of many

ICE converted EVs. Other firms are developing and installing regenerative braking systems in their vehicles. The authors found regenerative braking quite capable of effortlessly braking EVA EVs. An unresolved question is whether such a modification is cost effective. The authors believe that it is an important safety feature and should be included with the vehicle if hydraulic brakes with enhanced master cylinders are not available.

Operators are trying innovative techniques to improve their maintenance capabilities. American Telegraph and Telephone, operating 20 GM BEV-1 vehicles at its Culver City, California location introduced new maintenance procedures because battery pack analysis had shown that unconditioned replacement batteries had an inadequate longevity.

> New procedures, which were instituted for replacing failed batteries in the pack include preaging the batteries using ten discharge cycles, and selecting replacement batteries with voltage characteristics similar to other batteries in the pack [57:5].

American Telegraph and Telephone, General Telegraph and Telephone, Long Island Lighting Company, Con Edison and other site operators are using infra-red viewers to diagnose batteries. According to Louis Yanni of Booz, Allen & Hamilton the infrared viewer can be,

> used successfully to inspect electric vehicle battery packs for unusual thermal conditions which point towards the need for preventive maintenance. The device is particularly useful for instantaneous inspection of battery packs for loose battery cable

> connections or overheated batteries, without coming in contact with the battery [58:4].

A brief discussion of high-energy flywheel technology is in order. If it can be successfully developed, it could greatly improve acceleration and range characteristics of EVs. A good deal of theoretical research on flywheels has been done in the United States by D. Rabenhorst in 1969 (42), R. Guess and E. Lustenader in 1976 (22), and Captain David Ratcliff, USAF in 1979 (43). At present Japan is the only country which has an active hybrid vehicle demonstration program.

> One of the major fleets in use in the country is a fleet of eight hybrid trucks, operated by the Asahi Publishing Company's Steagaya Laboratory in Tokyo. The reason for the adoption of these hybrid trucks (instead of the usual diesel or gasoline-powered truck used in that industry) is noise control. These hybrid vehicles are operated in the electric mode while in a specified noise-sensitive zone and in a standard diesel mode elsewhere [55:p. xxii].

While there are not any hybrid vehicles being demonstrated in the USA today, NASA funding of basic research is advancing American know how in the important area of CVTs (15:20). ". . . Several research companies, including Kinergy Research and Development of Wake Forest, North Carolina are working on vehicles using such power supplies [9:4]." The authors have not given these vehicles further consideration because practical application of this technology in the USA within the next few years is unlikely.

Another interesting type of hybrid vehicle uses a petroleum fueled generator to recharge the batteries simultaneously during vehicle operation. The Electric Car Company of Dayton, Ohio uses this concept in powering converted Volkswagen Bugs. The authors believe this concept has merit. It is not developed in this thesis because there are no pickup sized vehicles using this concept currently available for purchase from US EV manufacturers.

CHAPTER 3

RESEARCH METHODOLOGY

In order to develop and illustrate a method of economic analysis, we must first discuss the general principles that will be employed. Since the Department of Defense emphasizes the use of life cycle costing in investment decisions, our methodology will be based on this principle. When utilizing life cycle costing, the future benefit or cost stream must be discounted to a single point in time for the comparison of investment alternatives. This process involves the concept of monetary time value. Reliability theory also relates to life cycle costing since it aids in the estimation of future maintenance costs, one of the elements of life cycle cost. In this chapter we will discuss these three concepts: the time value of money, life cycle cost and reliability theory.

Time Value of Money

Productive factors fall into three basic categories: natural resources, labor resources and capital goods. Natural resources are provided in a finite quantity by nature. Labor resources are made up of our social work force. These two factors are called primary productive factors. Capital goods, on the other hand, are referred to

as an intermediate production factor since they are produced by the economic system itself to be used as productive inputs for the further production of goods and services (45:598). The return received on natural resources for their use in the production process is termed rent. Similarly, the return on utilized labor is termed wages. The return that is realized on capital goods invested in the production process is termed interest (45:599). Interest is precipitated by both the productivity of capital and the fact that savers must be paid for abstaining from the present consumption of goods (45:613). Paul Samuelson says that people agree to transform the primary factors of production into intermediate capital goods, because "It is a technological fact of life that you can get more future consumption product by using indirect or roundabout methods [45:600]." In other words, people realize that by sacrificing current consumption and reinvesting these capital goods, they can enhance their future consumption by improving the productive capabilities of the production process. An important concept to understand is that "after allowing for all depreciated requirements, capital has net productivity (or real interest yield) that can be expressed in the form of a percentage per annum; and the only reason you do not take further advantage of this opportunity to get more product by roundabout method is that you would have to cut down on present consumption if you are to speed

up capital's rate of growth and future consumption [45:600]."
Thus a capital project has a net productivity and this is expressed in an annual percentage yield which you can earn by investing in it. This annual percentage yield is the rate of interest at which it would just pay to undertake it. Society can therefore exchange present consumption goods for future consumption goods at a trade-off rate depicted by the rate of interest (45:614).

There are several reasons an individual prefers present consumption to future consumption. The typical consumer has the expectation that future dollars will have a lower marginal utility because income will be higher in the future. Also there is a systematic time preference by consumers for present rather than future goods because of life's uncertainties, including death (45:613).

As is now evident, both society's impatience to consume, and the net productivity of capital interact to cause interest. Due to this concept of interest, the farther off in the future a given dollar receipt is, the less it is worth today. This fact leads us into the time value of money.

Money has a time value because of the opportunity cost to society of having funds tied up in an investment instead of having them free for other investments during that time period (18:4;5). "This phenomenon must be formally considered when selecting among alternative investment

opportunities [18:47]." Society's rate of time preference is the rate of interest (or discount rate) at which society is indifferent to receiving one dollar today or one dollar plus interest in one year. For example, if society were indifferent to receiving $1.00 now or $1.10 in one year, society's rate of time preference is 10% (36:191).

The concept of monetary time preference can be applied to future expenses as well as future receipts. Future expenses, just as future receipts, have present values determined by the rate of interest involved in the analysis. When considering alternate investment decisions, the time value of money must be taken into consideration by discounting the future expenditures by the discount rate to arrive at the present value of the future costs.

The Office of Management and Budget has mandated in OMB circular A-94 that a 10% discount rate will be utilized in any investment decision (62,4). This value reflects the government's estimate of the average rate of return on private investment before taxes and after inflation, and reflects the government's rate of time preference for money (62,4). The Department of Defense feels the 10% discount rate reflects the preference for current and future money sacrifices that the public exhibits in non-government transactions (53,9). There is some argument as towhether or not 10% is the correct value to be used in present value analysis, but that argument is beyond the scope of this

thesis given our mandated figure of 10% in government regulations.

Present value analysis is a method of evaluating alternative investment opportunities that takes into consideration society's, or in this case, the government's time preference for money. Realizing the benefit of this method in evaluation of alternative investments, the Department of Defense has stated that all economic analyses will use the present value technique to promote greater disclosure of, and consistency in, identifying the resource implications of proposed Department of Defense investments (53:9). Present value analysis involves reducing a future cost or benefit stream to a single value, at a specified point in time, for comparison with alternative investments (36:89). In equation form, given a stream of costs, C_1, C_2, . . . C_n, a salvage value at the end of n years, S_n, and an original capital outlay C_o, the present cost, PC, is given by:

$$PC = C_o + \frac{C_1}{(1 + r)^1} + \frac{C_2}{(1 + r)^2} \ldots + \frac{C_n}{(1 + r)^n} - \frac{S_n}{(1 + r)^n}$$

$$\text{or Symbolically:} \quad PC = \sum_{t=o}^{N} \frac{C_t}{(1 + r)^t} - \frac{S_n}{(1 + r)^n}$$

where r is the rate of discount (10% in Department of Defense investment analysis) and n is the number of years in the analysis period (36:190). Note that the salvage value of the investment at the end of the analysis period is

treated as a negative cost in the nth year and discounted to the present for inclusion in the net present cost of the investment. This accounts for the positive cash flow incurred by the sale of the investment at the end of the analysis period. This must be included in the analysis because it will offset some of the costs incurred during the investment period thereby reducing the cost of the investment.

If all alternative investments meet the requirements set by the investor, they must be evaluated to determine the alternative providing the least present cost for selection. The Department of Defense sets this selection criteria in DODI 7041.3: "When alternative investment proposals for achieving a given mission objective have the same level of expected benefits, the alternative with the lowest discounted cost or lowest uniform annual cost should be preferred." By following this policy the Department of Defense in effect and indirectly frees the excess funds for other investment uses, an important consideration in the resource constrained environment we operate in. Present value should be used in this analysis because even though the rate of discount is the same for all alternative investments, the year in which the costs occur and the amount of these costs are likely to vary, hence the present costs will vary (36:226). An example of present value application will illustrate the effect of the time value of money.

Figure 3-1. Present Value

OPTION	INITIAL COST	COST PER YEAR OF LIFE 1	2	3	SALVAGE VALUE
A	1,000,000	100,000	20,000	0	100,000
B	1,000,000	0	20,000	100,000	100,000

$$\text{Present Value} = C_o + \frac{C_1}{(1+r)} + \frac{C_2}{(1+r)^2} + \frac{C_2}{(1+r)^3} + \frac{S_3}{(1+r)^3}$$

Present Value A = 1,000,000 + 90,910 + 16,530 = 75,130 =
$1,032,310.00

Present Value B = 1,000,000 + 16,530 + 75,130 = 75,130 =
$1,016,530.00

Consider the two alternative investment options A and B in Figure 3-1. Both investment alternatives require an initial capital outlay of 1 million dollars. Similarly both alternatives have a three year life and a $100,000 salvage value at the end of three years. Both alternatives require $120,000 in outlays during their three year life but option A requires outlays of $100,000 in the first year and $20,000 in the second year while option B requires outlays of $20,000 in the second year and $100,000 in the third year. When present value analysis is applied, option A has a present cost of $1,032,310.00 while option B has a present cost of $1,016,530.00; a difference of $15,780.00, making option B the favored investment alternative. This difference is due to the time value of money associated with the costs of the

investments occurring at different times during their three year life. This example illustrates the necessity of utilizing present value analysis in any economic analysis of alternative investments.

Life Cycle Costs

The Department of Defense operates in an environment characterized by scarcity of resources. Annual Congressional appropriations impose a spending constraint on the Department of Defense, necessitating rigorous control to ensure enough resources are available to fund mission essential projects. The control of cost is especially important in procurement since the cost of systems and products has been increasing due to inflation and cost growth (4:2). In order to conserve resources when buying defense hardware, the federal government generally selects the lowest bidder in any contract competition (46:1). In recent years, the Department of Defense has realized more fully that the purchase price of a product represents only part of its total cost (46:1). Other costs involved in the total cost of a system throughout its life are research and development cost, production and construction cost, operation and support cost, and retirement and disposal cost (4:10). These costs when added together form the life cycle cost of the system or product.

In his book "Design and Manage to Life Cycle Cost", Blanchard defined life cycle cost as: ". . .all cost associated with the system or product and applied to the defined life cycle (4:9)." Seldon expands this definition of life cycle cost,

> The life cycle cost of an item - its total cost at the end of its lifetime-includes all expenses for research and development, modification, transportation, introduction of the item into inventory, new facilities, operation, support, maintenance, disposal, and any other costs of ownership, less any salvage revenue at the end of its lifetime [46:9].

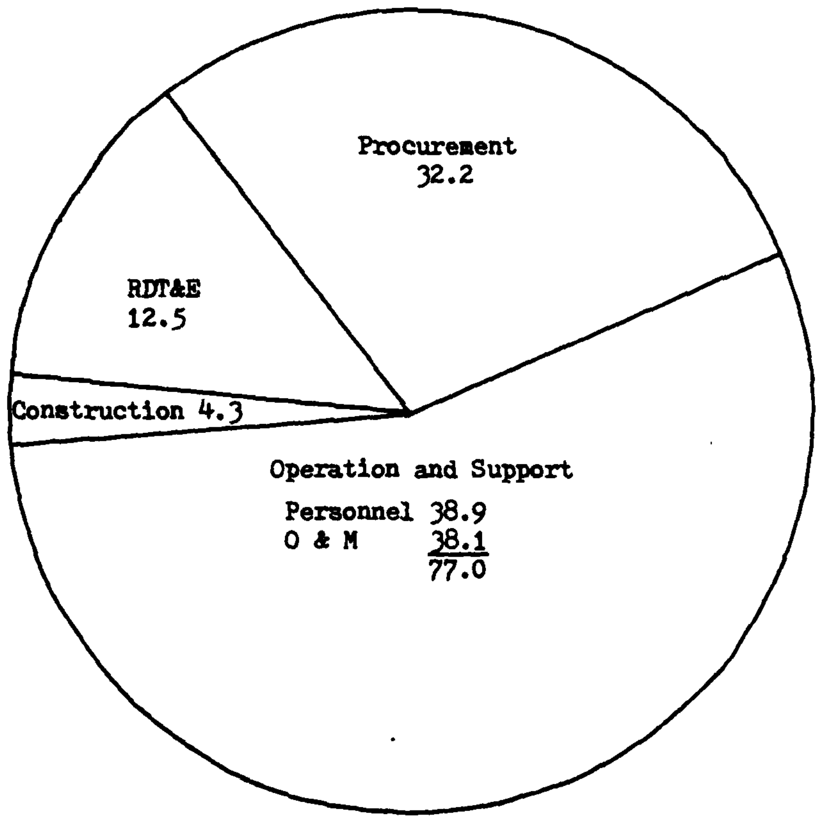
Our operational definition of life cycle cost is outlined in a government systems acquisition guide, "The life cycle cost of a system is a total cost to the Government of acquisition and ownership of that system over its full life. It includes the cost of development, acquisition, operation, support and where applicable disposal [54:p. 1-1]."

The concept of life cycle cost takes into account the fact that the total cost of a system throughout its life is sensitive to design features of reliability (46:81). Small increases in acquisition cost may yield significant reductions in operation and maintenance costs thereby reducing life cycle cost (46:4). The Department of Defense has realized that a low purchase price frequently means high operation and support costs for a system (46:2). Also, these ownership costs, operation and support or maintenance, frequently far exceed procurement costs and have therefore imposed strict limits on the amount of

equipment that could be purchased (46:1). Figure 3-2 illustrates the impact of operation and support costs on the defense budget. In 1979, operations and support accounted for over 61% of the Department of Defense budget. This fact emphasizes the necessity of considering the future operation and support costs involved with a procurement action. Since the selection of the lowest purchase price in a contract competition may turn out to be a false economy, and the objective of life cycle costing is to choose the best way to employ scarce resources (4:II), life cycle costing is regarded as a better criterion than purchase price for government procurement (46:3).

Life cycle costing is a method of economic analysis that takes the total costs of a system into consideration. All the costs involved with a system throughout its life are added together to determine the life cycle cost of that system. This figure is compared to life cycle costs associated with other systems that operate with the same level of performance to determine the low cost alternative. Blanchard points out that the time period involved in the analysis does not have to be the total physical life of a system. A shorter time period often referred to as the "economic life" may be used if this time period is more relevant to the analysis in question (4:13). It must be pointed out, however, that in order to perform an economic analysis using life cycle costing, all alternatives must be

Figure 3-2. 1979 DOD Budget (billions of dollars)



Blanchard, Benjamin S. Design and Manage to Life Cycle Cost. Portland, Oregon: M/A Press, 1978.

evaluated over the same period of time; the length of time is irrelevant but it must be the same for all alternatives. Life cycle cost analysis makes it possible to compare the costs of a number of alternative ways of meeting an operational requirement (46:II).

To illustrate the concept of life cycle costing, consider two investment alternatives; option A and option B listed in Figure 3-3.

Figure 3-3. Life Cycle Cost

OPTION	PURCHASE PRICE	OPERATION COST/YR.	MAINTENANCE PER YR.	SALVAGE VALUE	YRS OF LIFE
A	19,000	100	150	1,000	10
B	17,000	300	250	500	10

LIFE CYCLE COST A = 19,000 + (100)10 + 50(10) - 1,000 = 19,500

LIFE CYCLE COST B = 17,000 + 300(10) + 250(10) - 500 = 22,000

Option A has a purchase price of $19,000.00, and option B has a purchase price of $17,000.00. If a simple price comparison is used when deciding between these investment alternatives, option B would be selected. If a life cycle costing approach is used, however, one notices that option B costs 200 dollars more per year to maintain and 200 dollars more per year to operate. Option B is also worth 500 dollars less as salvage at the end of its 10 year life.

These added costs (and less salvage revenue) more than offset the higher purchase price of option A. Utilizing life cycle costing, option A would be selected over option B since it will save the investor $2,500.00 over the 10 year life of the investment.

This is a simple example, obviously, and the reader must realize that in any utilization of life cycle costing, present value analysis must be applied to take into consideration the time value of money associated with project costs occurring in future years. Even without the application of present value analysis (which was discussed in the previous section) this is a good example of the application of life cycle costing.

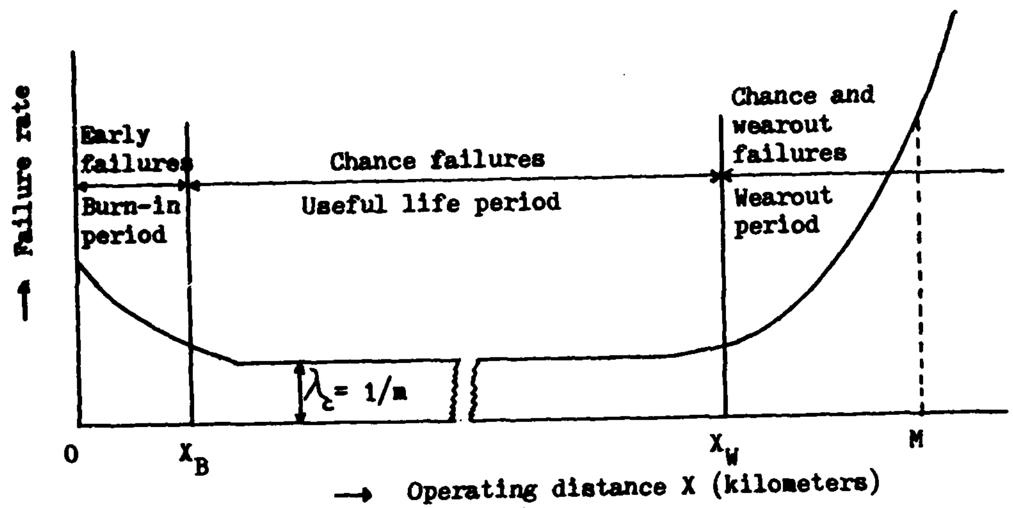
The Department of Defense realizes the benefits of life cycle costing and directs its use in the procurement process. A 1973 system acquisition guide states: "Virtually all decisions should be made taking life cycle cost into account (54:p. 2-1)." Because of the need to reduce the total cost of a system to the Department of Defense, and the emphasis the Department of Defense places on the use of life cycle costing in the procurement process, the authors will utilize life cycle costing in our economic analysis of electric vehicles.

Reliability Theory

The ensuing discussion on reliability is adapted from Igor Bazovsky's book, Reliability Theory and Practice (3). His work is important because it provides maintenance managers with a theoretical framework for understanding equipment malfunctions. Four major electrical systems, batteries, chargers, controllers, and motors are important elements of EV reliability. Knight, Jervis, and Herd define reliability as ". . . the probability of a device performing its purpose adequately for the period of time intended under the operating conditions encountered [31]." Initially we will consider the individual component, then expand upon component reliability concepts to show how aggregate reliability is derived.

The Electric Component Life Cycle. Figure 3-4 shows that electric systems typically have three distinct periods in their life cycle, burn-in, useful life, and wearout. It can be shown that electric system malfunctions typically follow an exponential distribution during their useful life period, then become normally distributed during their wearout period. During the burn-in period components are failing due to technological problems or infant mortality. Component failures reach their lowest level during the useful life of a system. Failures which do occur are chance malfunctions, rather than age related. Components fail due to age-related fatigue during the wearout period.

Figure 3-4. Electric Component Reliability as a Function of Distance



Bazovsky, Igor. Reliability Theory and Practice. Englewood Cliffs NJ: Prentice-Hall, Inc. 1961, p. 33.

The U.S. Postal Service (USPS) has found the model illustrated in Figure 3-4 appropriate in their research of EV electrical components (55:p. A-12), and it provides the basis for our discussion.

Derivation of the Reliability Function. Consider first an individual component, a controller, as an illustrative medium for derivation of the reliability function, R(X). In an arbitrarily chosen 2,000 kilometer (1,242.8 mile) operating interval, failure or survival of the controller are mutually exclusive events; the battery will either survive or it will fail. Reliability of the controller is contingent on its surviving the arbitrarily chosen 2,000 kilometer interval. The expected failure rate is the same for every randomly chosen interval. The reliability function is:

$$R(X) = e^{-\lambda_c X} \qquad (1)$$

where λ_c = chance failure rate

X = interval of time, distance or cycles

Bazovsky says that this formula is valid for ". . . all properly debugged devices which are nct subject to early failures, and which have not yet suffered any degree of wearout damage or performance degradation because of their age [3:1]." If the controller meets the above criteria the following examples are valid:

Example 1: The reliability of the controller for any 200 kilometer (124.3 mile) operation over an arbitrarily chosen 2,000 kilometer interval, given λ_c = .00002 is:

$$R(X) = e^{(-.00002)\ (200)} = .996$$

Example 2: The probability that the controller will survive throughout an arbitrarily chosen 2,000 kilometer interval is:

$$R(X) = e^{(-.00002)\ (3,000)} = .961$$

The mean kilometers between failure, $m = 1/\lambda_c$. Therefore, equation 1 could be rewritten:

$$R(X) = e^{-X/m} \qquad (2)$$

A component will either survive or fail over an interval chosen at random during the useful life of the vehicle. This fact allows us to derive the survival function,

$$S(X) = {}^{N_s}/_{N_o} = e^{-\lambda_c X} \qquad (3)$$

Where N_s = Number of components of a population which survive operation over a randomly chosen interval during the useful life of the vehicle.

N_o = total number of components in the population

X = distance driven

m = mean kilometers between failure

The failure function, F(X), is similarly derived:

$$F(X) = {}^{N_f}/_{N_o} = 1 - e^{-\lambda_c X} \tag{4}$$

Where N_f = number of components of a population which fail during operation over a randomly chosen interval during the useful life of the vehicle. Survival or failure are mutually exclusive events. Therefore,

$$S(X) + F(X) = 1 \tag{5}$$

If one expresses equation 5 in terms of S(X) and substitutes equation 4 for F(X) one can now say:

$$S(X) = 1 - {}^{N_f}/_{N_o} \tag{6}$$

If one takes the derivative of S(X) with respect to X, equation 6 is rewritten:

$$\frac{ds(X)}{dX} = 0 - \frac{1}{N_o} \quad \frac{dN_f}{dX} \tag{7}$$

If one multiplies both sides of equation 7 by N_o, equation 7 is rewritten:

$$\frac{dN_f}{dX} = -N_o \frac{dS(X)}{dX} \tag{8}$$

One can now express equation 8 in terms of the failure rate due to chance failures, λ_c, as follows:

$$\lambda_c = -\frac{N_o}{N_s} \frac{dS(X)}{dX} \tag{9}$$

Equation 9 is rewritten as follows, since $-\frac{N_o}{N_s}$ is the negative reciprocal of S(X):

$$\lambda_c = -\frac{1}{S(X)} \frac{dS(X)}{dX} \qquad (10)$$

If one multiplies both sides of equation 10 by the negative derivative of X, -dX, equation 10 is rewritten:

$$-\lambda_c dX = \frac{dS(X)}{S(X)} \qquad (11)$$

Next, integrate both sides of equation 11 between zero and any distance X:

$$\int_0^X \lambda_c dX = -\int_0^X \frac{dS(X)}{S(X)} \qquad (12)$$

Equation 12 can be simplified to the following:

$$-\lambda_c X = \ln S(X) \qquad (13)$$

By taking the natural logrithm of both sides, equation 13 becomes:

$$S(X) = e^{-\lambda_c X} \qquad (14)$$

Similarly,

$$F(X) = 1 - e^{-\lambda_c X} \qquad (15)$$

Equation 14 represents the probability of component survival over any interval X during its useful life. Henceforth the survival function, S(X), will be referred to

as the reliability function, $R(X)$. Equation 15 is the probability of component failure over any interval X during its useful life. Remember that $R(X)$ and $F(X)$ are only valid models of component behavior during their useful life period, as depicted in Figure 3-4.

<u>Reliability Theory Implications for Single Electric Components</u>. Failures become normally distributed during the wearout phase and are characterized by failures occurring due to age-related fatigue. Components which fail during the wearout phase are often irreparable and must be condemned. Maintenance policy should be to retard entry of the EV into the wearout period through periodic functional checks, preventive maintenance, and selective replacement of inexpensive components as they approach the wearout point, X_w. M, the mean life, also depicted in Figure 3-4, is that point at which half of the components in a population have failed. σ is the standard deviation of the failures about M. "The transition from exponential behavior to wearout behavior, occurs for a single component at an age between $M - 3.0\sigma$ and $M - 3.5\sigma$ [3:53]." Certainly, component maintenance should be at a suitable interval from the mean life, M, to prevent a large number of failures due to wearout.

$R(X)$ takes the form of the exponential function, as is depicted in Figure 3-5. Manipulation of $R(X) = e^{-\lambda_c X}$ shows that the chance of an individual

component surviving until the mean distance (or cycles) between failure is only .368. For example, take a battery whose mean cycles between failure, m, is 800 recharging cycles. Recall that $\lambda_c = 1/m$. For our example $\lambda_c = 1/800 = .00125$. If one wishes to determine the probability of a battery surviving until m, our operating interval, X, is 800 cycles. Therefore,

$$R(X) = e^{(-.00125)\ (800)} = e^{-1} = .368 \qquad (16)$$

Further manipulation of R(X) shows that the mean life of components in a population, M, is much shorter than m:

$$R(X) = e^{(-.00125)\ M} = .500 \qquad (17)$$

One finds that the mean life of batteries in a population with $\lambda_c = .00125$ is 462 cycles when one solves equation 17 for M.

EV component reliability is characterized by the reliability function, R(X), in the useful life period. For this distribution one must realize that:

> . . .in the exponential distribution about 63 percent of the failures occur in operating times shorter than the mean time between failures, and about 36 percent of the failures occur only after operating times longer than the mean time between failures. . . In the exponential distribution the frequency of failures is higher towards the shorter operating times. Therefore, reliable operations can be achieved only for operating times much shorter than the mean time between failures. Only for operating times that are short compared with m do low probabilities of failures exist, and therefore high probabilities of failure-free operation [3:37].

The failure density function, f(X), is the first derivative of R(X).

$$R(X) = e^{-\lambda_c X} \tag{18}$$

$$F(X) = \frac{dR(X)}{dX} = \lambda_c \; e^{-\lambda_c X} \tag{19}$$

The integral of f(X) from zero to infinity is unity. This may be interpreted to mean that every component will fail at some point in the future.

$$\int_0^X f(X)dX = \int_0^X \lambda_c e^{-\lambda_c X} dX = -\frac{\lambda_c}{\lambda_c} \; e^{-\lambda_c X}\Big]_0^X = 1 \tag{20}$$

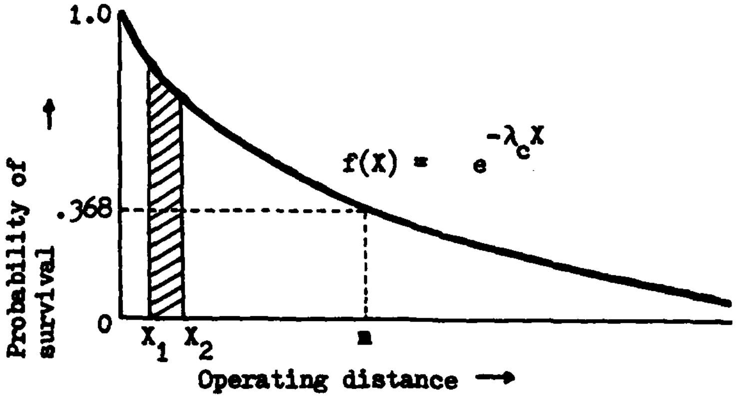
This integral is also called the exponential cumulative probability of failure, Q(X).

$$Q(X) = \int_0^X \lambda \; e^{-\lambda_c X} dX = -1 \; e^{-\lambda_c X}\Big]_0^X = 1 - e^{-\lambda_c X} \tag{21}$$

Figure 3-6 is a graph of the exponential cumulative probability of failure.

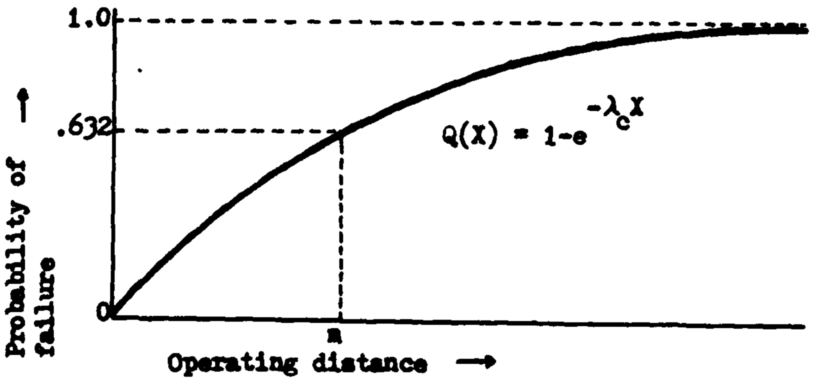
Q(X) is the theoretical basis for our claim that about 63 percent of the components in a population fail by the mean distance between failures, m. Consider a battery charger with a chance failure rate, λ_c, of λ_c = .00002. Since λ_c = 1/m, the mean distance between failures, m, equals 50,000 kilometers (31,070 miles). We evaluate Q(X) to show that approximately 63 percent of the battery

Figure 3-5. The Exponential Function



Bazovsky, Igor. Reliability Theory and Practice.
Englewood Cliffs NJ: Prentice-Hall, Inc. 1961, p. 38.

Figure 3-6. Exponential Cumulative Probability of Failure Curve



Bazovsky, Igor. Reliability Theory and Practice.
Englewood Cliffs NJ: Prentice-Hall, Inc. 1961, p. 39.

chargers in an EV fleet will fail before m:

$$Q(X) = \int_{0}^{m=50,000} .00002e^{(-.00002)\ (50,000)}\ dX = 1 - e^{-1} \qquad (22)$$

$$= 1 - .3679 = .6321 \cong .63 \qquad (23)$$

Figure 3-7, the graph of the normal figure distribution about the mean life, M, shows that selection of an overhaul interval, X_o, is important if we are to retard the tendency towards catastrophic component failures due to wearout. As the EV enters the wearout period, the component failure rate due to wearout, λ_w, becomes a factor in our selection of an appropriate X_o.

$$\lambda = \lambda_c + \lambda_w \qquad (24)$$

where λ = total failure rate

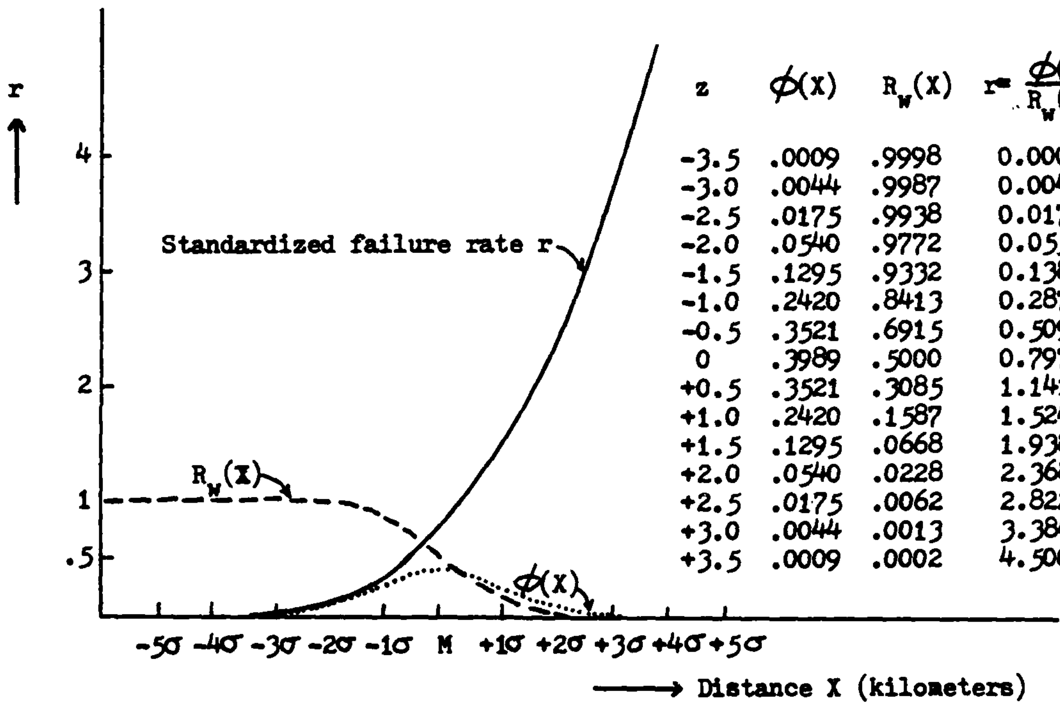
λ_c = failure rate due to chance

λ_w = failure rate due to wearout

During the wearout period, component failures begin to occur in a normal distribution, as depicted in Figure 3-7. Half of the components fail by the mean life, M, which lies much closer to the origin than the mean distance between failures, m.

Consider operation of an EV from distance X1 to distance X1 + X2. The overall failure rate is the sum of the chance failure rate and the wearout failure rate,

Figure 3-7. The Gaussian Normal Failure Rate During the Wearout Phase



z	$\phi(X)$	$R_W(X)$	$r = \frac{\phi(X)}{R_W(X)}$
-3.5	.0009	.9998	0.0009
-3.0	.0044	.9987	0.0044
-2.5	.0175	.9938	0.0176
-2.0	.0540	.9772	0.0553
-1.5	.1295	.9332	0.1388
-1.0	.2420	.8413	0.2877
-0.5	.3521	.6915	0.5092
0	.3989	.5000	0.7978
+0.5	.3521	.3085	1.1413
+1.0	.2420	.1587	1.5249
+1.5	.1295	.0668	1.9386
+2.0	.0540	.0228	2.3684
+2.5	.0175	.0062	2.8226
+3.0	.0044	.0013	3.3846
+3.5	.0009	.0002	4.5000

$\phi(X)$: Standardized wearout failure density function

$R_W(X)$: Probability of surviving wearout

$r(X)$: Standardized failure rate curve

Per kilometer failure rate: $\lambda_W = \frac{r}{\sigma}$

Wearout density function: $f(X) = \frac{\phi(X)}{\sigma}$

σ = Standard deviation in kilometers

Bazovsky, Igor. Reliability Theory and Practice. Englewood Cliffs NJ: Prentice-Hall, Inc. 1961, p. 44.

$\lambda = \lambda_c + \lambda_w.$

$$R(X) = e^{-\lambda_c X} \cdot \frac{RW\ (X1 + X2)}{RW\ (X1)} = \exp\ -\int_{X1}^{X1+X2} (\lambda_c + w)\, dX \qquad (25)$$

Equation 25 is integrated in two steps:

$$-\int_{X1}^{X1+X2} (\lambda_c + \lambda_w)\ dX = -\lambda_c X \int_{X1}^{X1+X2} \lambda_w\ dX$$

If we use the arithmetic mean to approximate $-\int_{X1}^{X1+X2} \lambda_w\ dX$, we obtain:

$$-\lambda_{wm} = -1/2\ \left[\lambda_w\ X1 + \lambda_w\ (X1 + X2)\right]$$

Therefore,

$$\int_{X1}^{X1+X2} \lambda_w\ dX = -\lambda_{wm}\ X$$

The combined reliability function in the wearout period is now:

$$R(X) = \exp\ -(\lambda_c + \lambda_{wm})X \qquad (26)$$

Equation 26 shows that reliability is partially a function of component wear. Vehicle maintenance personnel can reduce the number of failures by preventive maintenance at an appropriate distance before M, X_o. X_o is the distance interval for component overhaul and it should be chosen so that λ_{wm} is one magnitude smaller than λ_c. In practice this will happen when X_o is at least M - 3.0σ. When X_o is properly chosen the reliability function will be

approximated by $R(X) = e^{-\lambda cX}$, because the contribution of wearout to the overall failures will remain below 10 percent (3:51).

From our battery charger example $\lambda c = .00002$, $m = 50{,}000$ kilometers (31,070 miles) and $M = 34{,}657$ kilometers (21,536 miles). Assume maintenance data reveals that the standard deviation of wearout failures, σ, equals 2,000 kilometers (1,243 miles). The Z value of $\lambda_{wm} = .0002$ is $-3.5\,\sigma$. We must remove battery chargers at the $M - 3.50\sigma$ mark and replace them with overhauled or new battery chargers if we wish to prevent wearout failures from contributing to more than 10 percent of the failure rate. $M - 3.50\sigma$ is computed for the battery charger as follows:

$$M - 3.50\sigma = 34{,}657 \text{ KM} - 3.5\,(2{,}000) = 27{,}657 \quad (17{,}186 \text{ Miles}) \qquad (27)$$

If enough spares are provided, controllers and battery chargers could be routed to an avionics or communications repair center for overhaul. Air Force EV fleet operators could manage these components under the Repair Cycle Asset System. If the EV fleet operator does not have electronics repair capabilities, such a replacement policy could well be too expensive to afford. However, reliability theory tells us that if one waits to replace components when they fail, wearout failures will increase at an increasing rate.

As a result one will find EVs increasingly down for maintenance.

If components are replaced with new or overhauled components at X_o, it is possible to estimate the kilometers of failure-free operation which will result, Xavg. Assume that battery chargers are treated as repair cycle assets and overhauled by a work center in the Base Communications Squadron at X_o = 27,657 kilometers. If this is done, progression of the battery charger into the wearout period is averted and $R(X) = e^{-\lambda_c X}$ continues to be a good approximation of the reliability function. Recall that $m = 1/\lambda_c$ = 50,000 kilometers.

$$R(X_o) = e^{-X_o/m} \tag{28}$$

$$Xavg = \int_0^{X_o} R(X)dX = \int_0^{X_o} e^{-X_o/m}\, dX = -m\left[e^{-X_o/m}\right]_0^{X_o} \tag{29}$$

$$= m(1 - e^{-X_o/m}) = m\ Q(X_o) \tag{30}$$

Therefore,

$$Xavg = 50{,}000\ (1 - e^{-27{,}657/50{,}000})$$

$$= 21{,}243 \text{ kilometers } (13{,}200 \text{ miles}) \tag{31}$$

Failure to replace the battery charger at X_o will result in Xaug 21,243 kilometers.

<u>Battery Pack Maintenance</u>. Until now we have only considered one component in the EV system. When determining

reliability of the EV system, a combined reliability function must be computed. The combined reliability function, R(X), is the product of surviving chance failure, $e^{-\lambda cX}$, times the probability of surviving wearout, Rw(X).

$$R(X) = (e^{-\lambda cX})\ Rw(X) \tag{32}$$

Rw(X) models system failure inthe wearout phase and can be approximated by the normal distribution:

$$Rw(X) = \frac{1}{2} \int_{\sigma}^{X} e^{-(X - M)^2/2\ ^2}\ dX \tag{33}$$

Equation 33 is the integral for the normal distribution. One must use the normal distribution table to determine Rw(X). Accordingly, equation 33 simplifies to:

$$Rw(X) = Z\ \frac{X - M}{\sigma} \tag{34}$$

Where X = operating interval

M = mean life

σ = standard deviation of failures about M

For values less than $\pm\ 4\sigma$ mathematical tables are sufficient. When determining $M - 5\sigma$ or $- 6\sigma$ for the purpose of scheduling overhauls and estimating system reliability, mathematical tables with greater accuracy are required.*

*One such reference is US Department of Commerce, National Bureau of Standards. Table of Probability Functions Vol II, Second ed. US Govt Printing Office, 1948.

Consider first the reliability of a single battery. $M = 200$ recharging cycles, $m = 800$ recharging cycles, $\lambda_c = .00125$ and $\sigma = 40$. Three probabilities must be computed to derive a reliability curve, for a battery. These probabilities are the probability of surviving chance failure, $e^{-\lambda_c X}$, the probability of surviving wearout failure, $R_w(X) = Z \frac{X - M}{\sigma}$, and the combined reliability function,

$$R(X) = e^{-\lambda_c X} \cdot R_w(X). \tag{35}$$

If one computes these probabilities, the values in Table 3-1 are obtained. Figure 3-8 is a graph of the reliability curve for the battery. One sees from this graph that M shifts leftward from M_o to M_1 because $R_w(X)$ begins to adversely affect the combined reliability function, R(X) at $-3.0\,\sigma$ or 80 cycles.

Consider the system reliability of a battery pack of 20 batteries of the type for which we examined R(X). One must consider variations of $e^{-\lambda_c X}$ and $R_w(X)$, the system probability of surviving chance failure, $e^{-i\lambda_c X}$, and the system probability of surviving wearout failure, $R_w(X)^i$ in computing the system reliability function, $R_s(X)$:

$$R_s(X) = e^{-i\lambda_c X} \; R_w(X)^i \tag{36}$$

where $i = 20$, the number of batteries.

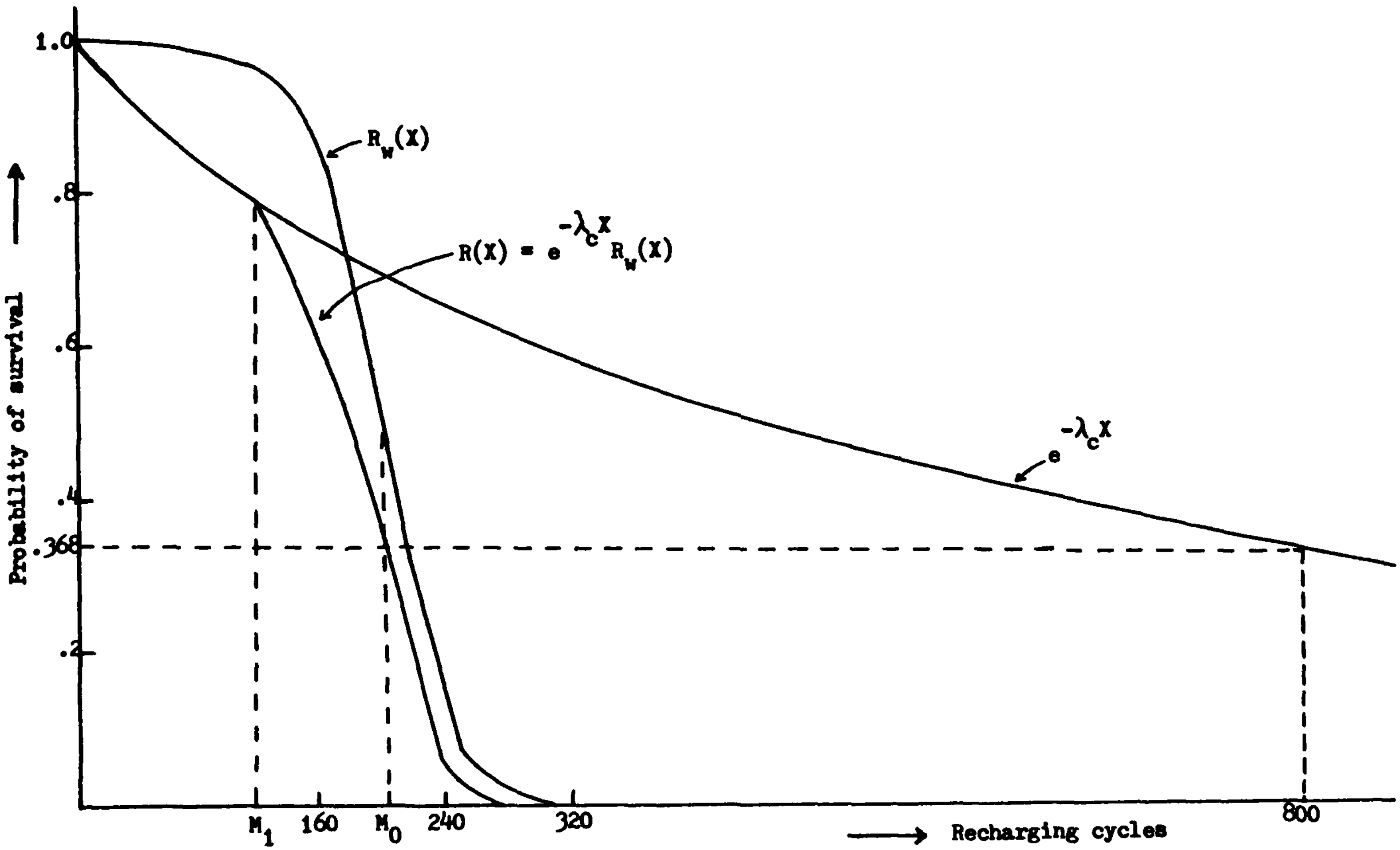
Computations for derivation of the system reliability function, $R_s(X)$, are contained in Table 3-2.

TABLE 3-1

COMPUTATIONS FOR DERIVATION OF THE COMBINED RELIABILITY FUNCTION

X (Cycles)	$e^{-\lambda_c X}$	$R_w(X)$	σ	R(X)
10	.9876	.99999999	-4.75	.9876
14	.9827	.99999984	-4.65	.9827
20	.9753	.99999966	-4.50	.9753
30	.9632	.99999893	-4.25	.9632
60	.9277	.9998	-3.50	.9275
120	.8607	.9773	-2.00	.8412
160	.8187	.8413	-1.00	.6888
200	.7788	.5000	0	.3894
240	.7408	.1587	+1.00	.1176
280	.7047	.0028	+2.00	.0161
320	.6703	.0013	+3.00	.0009
370	.6376	.00000107	+4.25	.0000

Figure 3-8. Reliability Curve for a Single Battery in a System



Bazovsky, Igor. Reliability Theory and Practice. Englewood Cliffs NJ: Prentice-Hall, Inc. 1961, p. 53.

TABLE 3-2

COMPUTATIONS FOR DERIVATION OF THE

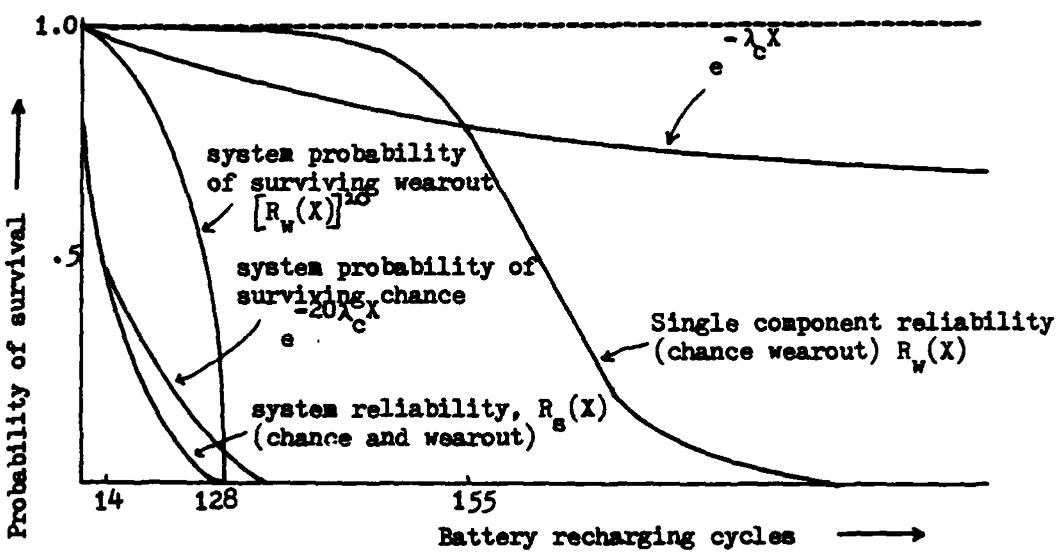
SYSTEM RELIABILITY FUNCTION

X (Cycles)	$e^{-\lambda_c X}$	$e^{-20\lambda_c X}$	RW(X)	$RW(X)^{20}$	σ	$R_s(X)$
10	.9876	.7788	.99999999	.999998	-3.74	.7788
14	.9827	.7047	.99999984	.999968	-4.65	.7047
20	.9753	.6065	.99999966	.999932	-4.50	.6065
30	.9632	.4724	.99999893	.999786	-4.25	.4723
60	.9277	.2231	.9998	.9960	-3.50	.2222
120	.8607	.0498	.9773	.6318	-2.00	.0315
160	.8187	.0183	.8413	.0316	-1.00	.0005
200	.7788	.0067	.5000	.0000	0	.0000
240	.7408	.0025	.1587	0	1.00	0
280	.7047	.0009	.0228	0	2.00	0
320	.6703	.0003	.0013	0	3.00	0
370	.6376	.0001	.00000107	0	4.25	0

Figure 3-9 is a graph of the system reliability function and it demonstrates how $R_s(X)$ is reduced as compared to the combined reliability function for a single battery, $R(X)$. In our application, distance intervals will be chosen to study component reliability because users schedule maintenance based on odometer readings. In this section the interval chosen for battery reliability is the number of battery recharging cycles, a more accurate measure of battery performance.

Table 3-2 shows that one must do preventive maintenance on the battery pack every 10 cycles to achieve a 78 percent assurance of optimal performance, battery pack $R_s(X)$. Optimal performance is defined as proper performance of all batteries in the pack. Suboptimal performance results when one or more batteries in the pack have failed. The battery pack is analogous to a system in which all of the components are in a series. When one of the batteries in the pack fails, properly functioning batteries will try to compensate by discharging power at a faster rate. In the long run, excessive power discharge results in shorter life for these batteries. Table 3-2 also shows that if preventive maintenance is delayed to every 30 cycles, $R_s(X)$ drops to 47 percent. One is tempted to delay maintenance on the battery pack until the EV is unable to perform its mission rather than perform preventive maintenance every 10 days, as this example calls for. However, delay of

Figure 3-9. The Reliability Curve for a Battery Pack



Bazovsky, Igor. Reliability Theory and Practice. Englewood Cliffs NJ: Prentice-Hall, Inc. 1961, p. 55.

preventive maintenance will cause system failures at an increasing rate.

Controller and Charger Maintenance

Preventive maintenance on controllers, and chargers will amount to overhaul of these components. Recall the controller whose m = 50,000 kilometers (31,070 miles). If one chooses to overhaul the controller every 20,000 kilometers (12,428 miles) and the distance at overhaul, X_o, is -5σ to -6σ from M, the controller will not be affected and its reliability operating between overhauls will be:

$$R(X_o) = e^{-X_o/m} \tag{37}$$

The reliability of the controller over the interval between overhauls is

$$R(X_o) = e^{-20,000/50,000} = .6703.$$

This means that if we had a population of 100 controllers, approximately 63 percent of them would survive until overhaul without failing. Since about 37 percent of the controllers would fail before X_o, the average distance between failures, Xavg, will be less than X_o:

$$Xavg = \int_0^{X_o} R(X_o)\ dX = m \left[e^{-X_o/m}\right]_0^{X_o} \tag{38}$$

$$= m(1-e^{-X_o/m}) = 50,000(1-e^{-20,000/50,000})$$

$$= 16,484 \text{ kilometers } (10,243.2 \text{ miles}) \tag{39}$$

If overhaul time were reduced from every 20,000 kilometers to every 10,000 kilometers (6,224.0 miles), $R(X_o) = e^{-10,000/50,000} = .8786$. The resultant $X_{avg} = \int_0^{X_o} R(X_o)\, dX = 50,000\ (1-e^{-10,000/50,000}) = 9063$ kilometers (5632.0 miles).

Vehicle fleet managers in the public sector are challenged with providing an acceptable service level at minimum total maintenance cost. In a limited EV fleet application, fixed costs for the motor pool remain relatively constant. Accordingly, the vehicle fleet manager tries to minimize total maintenance cost by focusing his efforts on finding the optimal balance between labor and materials costs. Determination of appropriate overhaul intervals is very important in this regard. The manager needs accurate information about the mean life, M, and the standard deviation of failures about M, σ, in determining an appropriate overhaul interval, X_o. If components are being overhauled too frequently, excessive labor costs will cause a suboptimal balance. If component overhauls are too seldom, wear-out failures will cause excessive materials costs. Excessive materials costs also result in a suboptimal balance. In our controller example, the vehicle fleet manager must determine an overhaul interval which results in acceptable component reliability at a minimum combined labor and materials maintenance cost.

If the fleet is driving 500,000 kilometers (310,070 miles) per year X_o = 20,000 kilometers will result in 500,000 kilometers/Xavg = 16,484 kilometers = 30 controllers overhauls per year. If X_o is reduced to 10,000 kilometers, the resultant controller overhauls per year will be 500,000 kilometers/Xavg = 9063 kilometers = 55 controller overhauls. If X_o = 20,000 kilometers is sufficiently far from M to prevent a significant number of controller failures due to wearout ($X_o = M - 5\sigma$ or -6σ), a further reduction of X_o from 20,000 kilometers to 10,000 kilometers will result in higher labor costs and only marginally improve reliability. The improved reliability would also probably exceed the service requirement. If X_o = 20,000 kilometers is less than $M - 3\sigma$, wearout failures could greatly increase materials costs if X_o were not reduced from 20,000 kilometers to 10,000 kilometers. Wearout failures increase maintenance costs because components must be condemned as irreparable. If wearout failures at X_o resulted in a high number of controller condemnation maintenance costs, the higher manhour costs associated with a reduction of X_o to 10,000 kilometers would be offset by the savings resulting from longer controller life.

Before the manager can determine the proper overhaul interval, the approximation of mean life, M, and the standard deviation, σ, must be accurate.

An extension of the time between overhauls is thus a question of the equipment's mean wearout life and of its standard deviation. Such extension, in order not to affect equipment reliability, requires that the mean wearout life of the equipment also be increased; otherwise, the reliability of the equipment may be dangerously reduced, especially during the operating hours just prior to overhaul [3:198].

Aggregate EV Electric System Reliability

Battery pack, charger, controller and motor reliability all have an impact on aggregate EV electric system reliability. These components are in a series; if any one of them fails, the EV is either operating suboptimally or it is inoperable. The aggregate reliability of the EV electric system, $R_A(X)$, is the multiple of the reliabilities of the individual components:

$$R_A(X) = R_B(X) \quad R_{CH}(X) \; R_{CR}(X) \quad R_M(X) \tag{40}$$

Where $R_A(X)$ = aggregate reliability of the EV electric system

$R_B(X)$ = reliability of the battery pack

$R_{CH}(X)$ = reliability of the charger

$R_{CR}(X)$ = reliability of the controller

$R_M(X)$ = reliability of the motor

Recall from our previous battery pack example, Table 3-2, that $R_s(X)$, the system reliability of the battery pack at 10 cycle overhaul period ($M - 4.75\sigma$) is .7788. One can use this probability in determination of $R_A(X)$, assuming that the EV travels an average of 40.0 kilometers

(24.9 miles) per discharge cycle. In this case, 10 discharge cycles would equal roughly 400.0 kilometers (248.6 miles).

Recall from equation 2 that

$$R(X) = e^{-X/m} \tag{41}$$

where X = the operating interval

m = the mean distance between failure

If the EV fleet manager has accurate estimates of m for the electrical components, $R_A(X)$ can be computed. Assume that accurate mean distances between failure have been determined as:

m_{CH} = 50,000 kilometers (31,070 miles)

m_{CR} = 35,000 kilometers (21,749 miles)

m_M = 100,000 kilometers (62,140 miles)

$R_A(X)$ is derived as follows:

$$R_A(X) = R_B(X) \quad R_{CH}(X) \quad R_{CR}(X) \quad R_M\,(X) \tag{42}$$

$$= (.7788)(e^{-400/50,000})(e^{-400/35,000})(e^{-400/100,000}) \tag{43}$$

$$= (.7788)(.9920)(.9886)(.9960) = .7607 \tag{44}$$

Thus the probability of zero defect EV operation over the 400 kilometer interval is roughly 76 percent. The most significant reliability factor in EV electric system reliability is battery pack reliability, $R_B(X)$.

EV electric system reliability, $R_A(X)$, can be modified to analyze the effects of preventive maintenance. Assume that the EV fleet manager has not had EVs long enough to know the mean distances between failure, m, for the electrical components. He is fairly confident that the mean distances between failure used in the previous examples are reasonable estimates of the actual values. Assume also that the data base is insufficient to estimate the standard deviation, σ, of failures about the mean life, M. Lacking this information, the manager must improvise an X_o which will, in all probability, prevent wearout failures from contributing to more tha 10 percent of component failures. If this condition holds, $R(X) = e^{-\lambda_c X}$, is a valid model of component reliability. The authors suggest that the manager overhaul components at intervals such that $R(X) = .95$ because they believe that R(X) will be a valid model if this is done. When accurate information about M and σ is obtained from maintenance data or other sources, the manager can establish new overhaul intervals based on this information.

Overhaul intervals required for the charger controller and motor are computed using equation 37. X_o for the charger is computed for illustrative purposes:

$$R(X_o) = .95 = e^{-X_o/m} \tag{45}$$

$$.95 = e^{-X_o/50{,}000} \tag{46}$$

$$\ln .95 - -X_o/50{,}000 \tag{47}$$

X_o = 2564.7 kilometers (1593.7 miles)

Slight modification of equation 47 allows computation of X_o for the battery pack which has say, 30 batteries, each with an m of 150,000 kilometers (93,210 miles).

$$R(X_o) = .95 - e^{-iX_o/m} \tag{48}$$

$$.95 = e^{-30X_o/150{,}000} \tag{49}$$

$$\ln(.95) = -30X_o/150{,}000 \tag{50}$$

X_o = 256.5 kilometers (159.4 miles)

Results for computations of $R(X_o)$ = .95 will result in the following X_os:

Component	X_o (kilometers)	X_o (Miles)
Charger	2,564.7	1,593.7
Controller	1,795.3	1,115.6
Motor	5,129.3	3,187.4
Battery Pack	256.5	159.4

If one wishes to compute the aggregate reliability of an EV electric system which has had component overhauls at the above intervals at 100,000 kilometers (62,140 miles) equation 44 must be slightly modified. The Xs used in the equation must represent distance traveled since last

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component overhaul. In our particular example the appropriate Xs would be as follows:

Component	X (kilometers)	X (Miles)
Charger	2541.5	1579.2
Controller	1258.5	782.0
Motor	2543.3	1580.4
Battery Pack	103.5	64.3

The probability of an electric system surviving until 100,000 kilometers given component overhauls at the computed X_os is computed below:

$$R_A(X) = R_B(X)\ R_{CH}(X)\ R_{CR}(X)\ R_M(X) \tag{51}$$

$$= (e^{-30(103.5)/150,000}) x (e^{-2541.5/50,000})$$

$$x(e^{-1258.5/35,000}) x (e^{-2543.3/150,000}) \tag{52}$$

$$= (.9795)(.9504)(.9647)(.9832) = .8845 \tag{53}$$

If components are overhauled at the suggested intervals and replaced when at the end of their useful lives, approximately 88 percent of EV electric systems will function defect free at the 100,000 kilometer mark. Individual components must be maintained at at least a 95 percent reliability rate if EV electric system reliability is to be kept at at least 80 percent or higher. The EV fleet manager must experiment with equation 51 to determine the EV electric system aggregate reliability rate possible given

maintenance funding. If a given level of EV electric system aggregate reliability is required, the EV fleet manager will want to experiment with equation 51 as a means of estimating cost of maintaining that service level.

The manager should schedule overhauls with the goal of increasing the useful life of the EV electric system. Though the cost of preventive maintenance tempts the manager to delay maintenance until components fail, wearout failures will shorten the useful life of EV components, increasing the EV life cycle cost. Component failures will also increase at an increasing rate, causing the service to drop below prescribed levels. Preventive maintenance will extend useful life of the EV electric system and ensure acceptable service to users. Remember also that the reliability principles discussed in this section can be beneficially applied to ICE vehicles in determining appropriate overhaul intervals which will extend the useful life of these vehicles.

CHAPTER IV

CONCEPTUAL APPLICATION AND DATA ANALYSIS

Data collection and data analysis formed the two phases of the research effort. Data was collected for the standard Air Force pickups operated by the 4950th Test Wing at Wright-Patterson Air Force Base, Ohio and for the American Motors DJ-5E Electrucks (EVs), which are capable of filling a flight line maintenance role. The research effort was channeled in two directions. First we determined the number of EVs required to provide the same service level as the 15 pickups serving maintenance personnel at the 4950th Test Wing. Then we compared the life cycle cost associated with a fleet of 15 standard Air Force pickups and the life cycle cost of the EV fleet, thereby determining the economic alternative for fleet replacement.

We first determined the number of EVs required to provide the present level of pickup service, realizing that EVs must be recharged after each sustained use and have an operating range limited to that of one discharge cycle per day. The Vehicle Operations Summary provided the information needed to calculate the expected distance the vehicle fleet was required to drive each day (Table 4-1). From this report we extracted the driving distance per month the

TABLE 4-1

DETERMINATION OF EV FLEET SIZE

Required Daily Driving Distance for EV Fleet

Month	Feb 80	Mar 80	Apr 80	May 80
Kilometers Driven by EV Fleet	22,778	18,367	14,525	15,510
Miles Driven by EV Fleet	14,154	11,413	9,026	9,638
Days in Month	28	31	30	31
Kilometers Driven per day	813.49	592.46	484.18	500.32
Miles Driven per day	505.50	368.16	300.87	310.90
	Jun 80	Jul 80	Aug 80	Sep 80
Kilometers Driven by EV Fleet	26,260	11,942	15,882	17,853
Miles Driven by EV Fleet	16,318	7,421	9,869	11,094
Days in Month	30	31	31	30
Kilometers Driven per day	553.48	385.24	512.31	595.11
Miles Driven per Day	343.93	239.39	318.35	369.80

TABLE 4-1 (cont.)

Month	Oct 80	Nov 80	Dec 80	Jan 81
Kilometers Driven by EV Fleet	15,552	10,948	12,866	14,770
Miles Driven by EV Fleet	9,664	6,803	7,995	9,178
Days in Month	31	30	31	31
Kilometers Driven per day	501.67	364.93	415.03	476.44
Miles Driven per day	311.74	226.77	257.90	296.06

Average Fleet Driving
Distance per day
  Kilometers per Day ÷ Months

6194.66 ÷ 12 = 516.22 kilometers/day (320.78 miles/day)

EV Vehicle Fleet Size
Average Fleet Driving
  Distance per day ÷ Estimated EV Range

516.22 ÷ 32.19 = 16.039 vehicles

16 EVs are required to provide the same service level as the present fleet of 15 ICE pickups.

Source: Vehicle Operations Summary. Wright-Patterson AFB, Ohio, February 1980 through January 1981.

vehicle fleet had been driven for the past 12 months. By dividing each figure by the number of days in that month we derived the distance per day driven by the vehicle fleet. We arrived at a daily driving requirement of 516.2 kilometers (320.8 miles) by taking an average of the daily driving requirements for each month (Table 4-1).

In order to calculate the expected size of the EV fleet needed to service the present transportation requirement we interviewed Mr. Ed Hansen, Vehicle Operations Manager for Consolidated Edison, and Mr. Frank Lucef, Electric Vehicle Fleet Engineer for the Long Island Lighting Company (34). Through these interviews the determination was made to utilize 32.2 kilometers (20.0 miles) per day as our estimated figure for EV range. This is a conservative estimate, but it takes into consideration the variability in range experienced during different seasons of the year, and will ensure that the EV fleet will meet its daily driving requirement even though there is bound to be some variability of the daily mileage requirement above our estimated figure. We calculated the expected size of the EV fleet by dividing the expected average daily fleet driving requirement (516 kilometers) by the expected daily range per EV (32.2 kilometers) giving us a fleet size of 16 EVs (Table 4-1).

With the EV fleet size computed, the life cycle cost of this EV fleet was determined. For our purpose the

life cycle cost was based on a ten year economic life, an arbitrary but suitable period for the analysis.

The life cycle cost of the pickup fleet is the sum of the present purchase price of the pickup fleet, the present value of the fleet maintenance costs for each year of the ten year analysis period, the present value of the fleet operating costs for each year of the ten year analysis period, minus the salvage value of the vehicle fleet at the end of the ten year analysis period. Ordinarily, the investment in spares inventory must be considered as an element of life cycle cost. In a contractor operated maintenance organization such as the one operated at Wright-Patterson AFB, Ohio, however, the spares inventory is maintained by the contractor. When a requirement exists for a spare part, the Air Force is charged accordingly by the contractor. This charge will naturally include a contribution toward any added inventory holding costs incurred by the contractor. Since these costs will be included in the maintenance cost of the vehicles, we do not have to address them separately.

The motor pool Vehicle Information System Monitor at Wright-Patterson AFB, Ohio, was interviewed to determine the purchase price of a standard Air Force pickup (51). This purchase price ($5,919.00) was multiplied by the 15 pickup trucks in the fleet to arrive at the purchase price for the vehicle fleet, $88,785.00 (Table 4-2).

TABLE 4-2

PURCHASE PRICE AND MAINTENANCE COST OF PICKUP FLEET

Price of standard Air Force pickup = $5919.00
No. of vehicles in pickup fleet = 15
Purchase price of pickup fleet = 5919.00 X 15 = $88,785.00

<u>Maintenance Cost of Pickup Fleet</u> (in dollars)
Determination of yearly maintenance cost estimates

Vehicle Year	Monthly Maint. Cost Jan 80	Feb 80	Mar 80	Apr 80	May 80	Jun 80	Jul 80	Aug 80
1971	60.55	1.45	94.43	14.94	65.33	218.21	101.08	9.97
1972	30.98	47.91	75.09	185.55	91.35	56.65	101.77	116.76
1973	77.02	74.38	96.60	137.90	77.95	98.83	97.38	95.60
1974	118.04	100.85	118.11	90.25	64.63	121.01	93.00	74.43
1975	72.99	74.73	55.99	70.98	74.42	96.16	120.73	79.54
1976	31.30	32.72	52.33	15.87	25.28	86.51	71.39	50.58
1977	23.83	53.55	37.84	32.23	38.93	54.26	48.29	27.31
1978	16.36	74.38	23.35	48.59	52.57	22.00	325.88	4.03
1979	9.29	6.77	25.58	0	94.34	26.25	3.59	15.24
1980	0	0	0	137.51	93.40	0	2.33	0

TABLE 4-2 (cont.)

Vehicle Year	Monthly Maint. Cost Sep 80	Oct 80	Nov 80	Dec 80	Yearly Maint. Estimate
1971	85.71	12.58	58.85	0	723.10
1972	185.72	98.27	54.07	122.48	1166.60
1973	164.46	78.26	68.05	99.83	1156.26
1974	143.20	58.25	82.03	77.18	1140.98
1975	45.07	68.07	67.59	83.57	909.84
1976	24.38	42.55	44.77	78.09	555.77
1977	37.75	30.25	32.55	58.49	475.38
1978	51.20	17.95	20.33	38.88	395.52
1979	7.60	1.00	1.99	36.11	227.75
1980	28.33	0	0	46.00	307.57

Present Value of the Maintenance Costs

Year of Analysis Period	1	2	3	4	5	6
Yearly Maint. Estimate	307.57	227.75	395.52	475.38	555.77	909.85
Present Value Factor	.90909	.9264463	.7513148	.6830135	.6209213	.5644739
Present Value of Main. Costs (PV)	279.61	188.22	270.11	324.69	345.09	513.58

TABLE 4-2 (cont.)

Year of Analysis Period	7	8	9	10
Yearly Maint. Estimate	1140.98	1156.26	1166.60	723.10
Present Value Factor	.5131581	.4665074	.4240976	.3855433
Present Value of Main. Costs (PV)	585.50	539.40	494.75	278.79

Present Value of the 10 year maintenance cost for 1 vehicle = PV = $3819.74

Present Value of the 10 year fleet maintenance cost = $3819.74 X 15 = $57296.10

Source: Vehicle Maintenance Management Report. Wright-Patterson AFB, Ohio. January 1980 through December 1980.

The present fleet of Wright-Patterson AFB pickups was separated into year groups (1971 through 1981 models) to derive the yearly fleet maintenance costs. We computed the average current maintenance cost for each year group by taking a monthly average of all the vehicles in each year group, then added these totals to arrive at a yearly average current maintenance cost for each year group (Table 4-2). We used the average current maintenance cost of the 1971 model pickups as an estimate for the maintenance cost of a vehicle in its tenth year since a 1971 model pickup operating in 1981 is ten years old. Using this same procedure for the other year groups (1972-1981), we arrived at an estimate of the maintenance cost for a pickup each year in the ten year analysis period (Table 4-2). Present value analysis was applied to these yearly maintenance cost estimates in order to remain consistent with the sound economic analysis procedures discussed in the previous chapter. The present value of a future cost is given by:

$$P = A \frac{1}{(1+i)^n}$$

where P is the present value of the future cost, A is the future maintenance cost, i is the rate of discount (fixed at 10 percent in our analysis by DODI 7041.3), and n is the year in which the cost is realized. By inserting the yearly maintenance cost estimates in this equation, we derived the present value of these future costs. We added

these figures to arrive at the present value of the maintenance costs for the 10 year economic life of a pickup, \$3,819.74. This figure was multiplied by the 15 pickups in the fleet to determine the present value of the fleet maintenance costs for the 10 year period, \$52,296.10. In equation form, the present value of the fleet maintenance cost is:

$$PM = 15 \left(\sum_{n=1}^{10} AMC_n \quad \frac{1}{(1+i)^n} \right)$$

where PM is the present value of the fleet maintenance cost, AMC is the annual vehicle maintenance cost, $\frac{1}{(1+i)^n}$ is the present value factor, and the constant signifies the 15 pickups in the fleet.

The Vehicle Operations Summary report was used to estimate vehicle operation cost. The monthly operating cost for each vehicle was determined by dividing the monthly operating cost for the fleet by the 15 pickups (Table 4-3). These monthly totals were added over a one year period to be used as a yearly estimate of the operating cost of a single pickup in each year of the analysis period. Present value analysis was applied to these yearly operating cost estimates, and these figures summed, to arrive at the present value of the operating costs for the 10 year economic life of a pickup, \$7,222.58. This figure was multiplied by the 15 pickups in the fleet to determine the present value of the fleet operating cost for the 10 year period,

TABLE 4-3

OPERATING COST, SALVAGE VALUE OF PICKUP FLEET,

AND LIFE CYCLE COST OF PICKUP FLEET

<u>Operating Cost of Pickup Fleet</u> (in dollars)
<u>Determination</u> of the estimated yearly operating cost for 1 vehicle

Month	Jan 81	Dec 80	Nov 80	Oct 80	Sep 80	Aug 80	Jul 80
Fleet Mthly Operating Cost	1946.06	1511.99	922.01	1531.86	1461.83	1313.23	1106.73
Number of Vehicles in Fleet	15	15	15	15	15	15	16
Average Monthly Vehicle Operating Cost (AMC)	129.74	100.80	61.47	102.12	97.46	87.55	69.17

TABLE 4-3 (cont.)

Month	Jun 80	May 80	Apr 80	Mar 80	Feb 80
Fleet Mthly Operating Cost	1550.47	1575.41	1707.81	1801.82	1798.74
Number of Vehicles in Fleet	16	16	16	16	16
Average Monthly Vehicle Operating Cost (AMC)	96.90	98.46	106.74	112.61	112.42

Yearly operating cost estimate for each vehicle = $\sum_{N=1}^{12} AMC_N = 1175.44$

The present value of the operating costs for 1 vehicle

Year of Analysis Period	1	2	3	4	5
Operating Cost Estimate	1175.44	1175.44	1175.44	1175.44	1175.44
Present Value Factor	.90909	.8264463	.7513148	.6830135	.6209213
Present Value of Operating Cost (PV)	1068.58	971.44	883.13	802.84	729.86

TABLE 4-3 (cont.)

Year of Analysis Period	6	7	8	9	10
Operating Cost Estimate	1175.44	1175.44	1175.44	1175.44	1175.44
Present Value Factor	.5644739	.5131581	.4665074	.4240976	.3855433
Present Value of Operating Cost (PV)	663.51	603.19	548.35	498.50	453.18

Present value of the 10 year operating cost per vehicle = $\sum_{N=1}^{10} PV_N$ = 7222.58

Present value of the 10 year fleet operating costs = 7222.58 X 15 = 108338.70

<u>Salvage Value of Pickup Fleet</u> (in dollars)

Estimate of pickup slavage value after 10 years = $250.00

Number of pickups in fleet = 15

Present value factor for year 10 = .3855433

Present value of fleet salvage value = ($250.00 X 15) X .3855433 = 1445.79

TABLE 4-3 (cont.)

Life Cycle Cost of 15 Vehicle ICE Pickup Fleet

LCC = Fleet Purchase Price + Fleet Maintenance Cost + Fleet Operating Cost - Fleet Salvage Value

LCC = $88,785.00 + $57,296.10 + $108,338.70 - $1445.79

LCC = $252,974.01

Source: Vehicle Operations Summary. Wright-Patterson AFB, Ohio. February 1980 through January 1981.

\$108,338.70 (Table 4-3). This process is illustrated in the following equation:

$$PO = 15 \left(\sum_{n=1}^{10} AOC_n \quad \frac{1}{(1+i)^n} \right)$$

where PO is the present value of the fleet operating cost, AOC is the annual vehicle operating cost, $\frac{1}{(1+i)^n}$ is the present value factor, and the constant designates the 15 pickups in the vehicle fleet.

In order to estimate the final element of the pickup fleet's life cycle cost, the salvage value, we contacted Ms. Louise Heddix (28) at the regional Defense Property Disposal Office, and arrived at an estimate of the average salvage value of a standard Air Force pickup after a ten year life, \$250.00. This figure was multiplied by the 15 pickups in the vehicle fleet to derive an estimate for the salvage value of the pickup fleet after the ten year analysis period. This figure was then multiplied by the present value factor associated with year 10 of our analysis period to determine the present value of this cash receipt at the end of the ten years (Table 4-3).

After obtaining these life cycle cost parameter estimates we computed the life cycle cost of the pickup fleet. The life cycle cost of the pickup fleet is given by the following equation:

$$LCC_f = (P+PM+PO) - PS$$

where LCC_f is the life cycle cost for the pickup fleet, P is the purchase price of the standard Air Force pickup fleet, PM is the present value of the fleet maintenance cost, PO is the present value of the fleet operating cost, and PS is the present value of the salvage value of the vehicle fleet after ten years. The computed life cycle cost of the pickup fleet is: $252,974.01 (Table 4-3).

The life cycle cost for the EV fleet was derived in a manner similar to that used for the pickup fleet. The fleet life cycle cost is comprised of the present cost of an EV fleet and the present value of the expected fleet maintenance and operating costs for each year of the ten year analysis period, less the salvage value of the EV fleet at the end of the ten year period.

The expected purchase price of the American Motors DJ-5E was determined by contacting American Motors General Corporation and obtaining an estimate for the current price of the DJ-5E Electruck. This estimate ($10,089.00) was multiplied by the 16 vehicles in the EV fleet to obtain a fleet purchase price of $161,424.00 (Table 4-4).

To obtain the annual operating cost per year for the EV fleet we extracted from the Vehicle Operations Summary the average number of kilometers driven by the 4950th Test Wing each year (Table 4-4). From the DJ-5E Electruck USPS Operating Results we determined the average electricity consumption rate for the DJ-5E Electruck to be

TABLE 4-4

PURCHASE PRICE AND OPERATING COST OF EV FLEET

Purchase Price of an EV Fleet

Estimated purchase price of one DJ-5E Electruck = $10089.00
Number of Pickups in EV fleet = 16
Estimated purchase price of a fleet of DJ-5E Electrucks = $10089.00 X 16 = $161,424.00

Operating Cost of an EV Fleet (in dollars)

Average yearly distance required of vehicle fleet = 186516.80 kilometers
Average electricity consumption rate for the DJ-5E = 1.0 kwh/km
Price per kilowatt hour of power = .0789 $/kwh
Estimated yearly operating cost for the fleet = 187597.36 X 1.0 X .0789 = $14716.18

Present Value of the Fleet Operating Cost

Year of Analysis Period	1	2	3	4	5
Estimated Yearly Fleet Operating Cost	14716.18	14716.18	14716.18	14716.18	14716.18
Present Value Factor	.90909	.8264463	.7513148	.6830135	.6204213
Present Value of Yearly Operating Cost (PV)	13378.35	12162.13	11056.48	10051.35	9137.59

TABLE 4-4 (cont.)

Year of Analysis Period	6	7	8	9	10
Estimated Yearly Fleet Operating Cost	14716.18	14716.18	14716.18	14716.18	14716.18
Present Value Factor	.5644739	.5131581	.4665074	.4240976	.3855433
Present Value of Yearly Operating Cost (PV)	8306.90	7551.73	6865.21	6241.09	5673.72

Present value of the fleet operating costs = $\sum_{N=1}^{10} PV_N = 90424.55$

1.0 Kwh/kilometer (1.6 kwh/mi) (Table 4-4). We contacted Dayton Power and Light and found the cost per kilowatt hour of electricity to be 7.89 cents. Using this data we computed the annual operating cost for the EV fleet by multiplying the consumption rate by the cost of electricity, and then we multiplied this total by the distance traveled annually by the fleet. In equation form:

$$AOC_f = CR(kwh/km) \times EC\ (¢/kwh) \times D(km/yr)$$

where AOC_f is the fleet annual operating cost, CR is the vehicle consumption rate in kilowatt hours per kilometer, EC is the cost of electricity in cents per kilowatt hour, and D is the distance traveled by the fleet per year. These annual operating costs are our estimates of the EV fleet operating costs that will occur in each year of the ten year analysis period (Table 4-4). Through these calculations we arrived at a figure of $14,716.18 to be utilized as our estimate of the EV fleet operating cost for each year of the ten year analysis period.

Present value analysis was applied to these annual operating costs by multiplying them by the present value factor discussed earlier, to obtain the present value of these costs for each year of the analysis period (Table 4-4). These costs were then added to determine the present value of the EV fleet operating cost. This relationship is expressed as:

$$PO = \left(\sum_{n=1}^{10} AOC_n \frac{1}{(1+i)^n} \right)$$

where PO is the present value of the fleet operating cost, AOC is the annual fleet operating cost, and $\frac{1}{(1+i)^n}$ is the present value factor. Through these computations we arrived at a figure of $90,424.55 for the present value of the fleet operating cost over the ten year analysis period (Table 4-4).

In order to determine the yearly maintenance costs for the EV fleet we used reliability estimates for four major components of an EV: the batteries, controller, charger and motor. These reliability estimates are listed in the DJ-5E Electruck USPS Operating Results (55:p. A-18).

We were able to determine X_o or the interval at which each component should be overhauled to maintain a desired reliability rate, $R(X_o)$, based on USPS chance failure rate estimates, λ_c, for these components. Charger, controller, and motor X_os were calculated based on a 95 percent chance that the components would survive until overhaul. This relationship is expressed as:

$$R(.95) = e^{X_o/m}$$

where R(.95) is the percent chance of survival over the operating interval, X_o is the overhaul interval, and m is the mean distance between failures. Interviews with EV fleet operators indicated that a check of the battery pack

every two weeks to ensure proper battery function and terminal connection is desirable. Since each EV in service with the 4950th Test Wing maintenance complex would have to drive approximately 32.2 kilometers (20.0 miles) per day, 7 days a week to provide the required service level, the X_o at the end of two weeks operation would be 450.6 kilometers (280.0 miles). The percent chance of survival until overhaul, $R(X_o)$, was determined for an overhaul interval of 450.6 kilometers using the relationship:

$$R(X_o) = e^{-\frac{iX_o}{m}}$$

where i is the number of batteries in series in the battery pack (there are 27) and m is the mean distance between failure for an individual battery. Results of the reliability calculations are summarized in Table 4-5.

We determined the years in which scheduled overhauls would occur by comparing the suggested overhaul intervals with the expected yearly driving distance per EV, 11,723.5 kilometers (7,285.0 miles). The expected number of overhauls for the EV fleet, depended on the probability of surviving until overhaul, $R(X_o)$, that was programmed. For chargers, controllers and batteries the actual number of overhauls would be approximately 5 percent greater than the scheduled number of overhauls because R(.95) was programmed. The actual number of battery pack overhauls would

TABLE 4-5

SUMMARY OF DJ-5E RELIABILITY CALCULATIONS

Component	Chance Failure Rate, λ_c	Overhaul Interval	Projected Number of Overhauls per Vehicle per Year	Probability of Survival until Overhaul, $R(X_o)$
Charger	.0000385	1,331.4 kilometers (827.3 miles)	8.81	.9500
Controller	.0000186	2,751.5 kilometers (1,710.0 miles)	4.26	.9500
Motor	.0000099	5,159.1 kilometers (3,205.9 miles)	2.27	.9500
Battery Pack	.0000675	450.6 kilometers (280.0 miles)	26.0	.9702

be approximately 3 percent greater than the scheduled number of battery pack overhauls because R(.97) was programmed. Results of the expected EV fleet electric system maintenance requirements calculations are summarized in Table 4-6.

Aggregate reliability theory application showed that the aggregate reliability of the EV electric system would be at least 80 percent for any operating interval if the suggested component overhaul intervals were adhered to. Aggregate reliability for the EV electrical system is determined based upon the operating interval chosen for study. As an example, the aggregate reliability of the DJ-5E electrical system for the first 7,000 kilometers (4349.8 miles) of its life was determined, assuming that scheduled maintenance was performed at the overhaul intervals recommended.

Reliability for the charger, controller, and motor was expressed by the relationship:

$$R(X_o) = e^{-x/m}$$

where X is the distance since the last overhaul and m is the mean distance between failures. If one uses the appropriate Xs for each component, and then substitutes the correct mean distances between failure into the above equation, the individual component reliabilities for the charger, controller, and motor are .9869, 9725, and .9819 respectively.

TABLE 4-6

EXPECTED EV FLEET ELECTRIC SYSTEM MAINTENANCE REQUIREMENTS

FOR A TEN YEAR LIFE CYCLE (16 EVS)

	Number of Overhauls/Year							
Component	Year 1	2	3	4	5	Total Scheduled Overhauls	Estimated Total Unscheduled Overhauls	Estimated Total Life Cycle Main. Requirement per Component
Charger	128	144	128	144	128	1344	67	1411
Controller	64	64	64	80	64	632	32	664
Motor	32	32	32	48	32	352	18	370
Battery Pack	416	416	416	416	416	4160	125	4285
	6	7	8	9	10			
Charger	144	128	144	128	128			
Controller	64	64	80	64	64			
Motor	32	32	48	32	32			
Battery Pack	416	416	416	416	416			

Reliability for the battery pack is expressed by the relationship,

$$R(X_o) = e^{-\frac{iX}{m}}$$

where i is the number of batteries in the battery pack. The reliability of the battery pack is .9840 for the interval in question.

Recall from equation 41 in Chapter III that the aggregate reliability equation for the EV electrical system is:

$$R_A(X) = R_{CH}(X)\ R_{CR}(X)\ R_M(X)\ R_B(X)$$

where $R_A(X)$ is the aggregate reliability of the EV electric system, $R_{CH}(X)$ is reliability of the charger, $R_{CR}(X)$ is reliability of the controller, $R_M(X)$ is reliability of the motor, and $R_B(X)$ is reliability of the battery pack. For our example:

$$R_A(X) = (.9869)\ (.9725)\ (.9819)\ (.9840) = .9272$$

The practical implication of this example is that the EV electric system has a 93 percent probability of proper functioning throughout the 7000 kilometer interval.

Through interviews with present EV fleet operators we derived an estimate of the yearly cost of scheduled and unscheduled component overhauls ($337.50) (23) which was

used with an estimate of the yearly chassis maintenance cost ($20.00) (51) as an estimate of the yearly maintenance cost for one EV (Table 4-7). In the case of batteries, these overhaul periods mandated a yearly purchase of a new battery pack per vehicle (999.00) (13). By adding the yearly component maintenance, chassis maintenance, and battery replacement cost we arrived at a yearly maintenance estimate for a single EV for each year of the ten year analysis period. The following equation illustrates this relationship:

$$AMC_n = CM_n + CHM_n + BR_n$$

where AMC_n is the annual maintenance cost for a single EV in year n, CM_n is the component maintenance cost in year n, CHM_n is the chassis maintenance cost in year n, and BR_n is the battery replacement cost in year n.

The yearly maintenance cost estimates ($1,356.50) were multiplied by the present value factor associated with each year in the analysis period to determine the present value of these future maintenance costs (Table 4-7). After the application of present value analysis, these costs were added together to determine the present value of the maintenance costs for an EV (Table 4-7). This relationship is expressed as:

$$PM = \left(\sum_{n=1}^{10} AMC_n \quad \frac{1}{(1+i)^n} \right)$$

TABLE 4-7

MAINTENANCE COST OF THE EV FLEET

<u>Maintenance Cost of an EV Fleet</u> (in dollars)
Present value of the maintenance cost for one EV

Year of Analysis Period	1	2	3	4	5
Estimated Component Main. Cost	337.50	337.50	337.50	337.50	337.50
Estimated Chassis Main. Cost	20.00	20.00	20.00	20.00	20.00
Battery Replacement Cost	---	999.00	999.00	999.00	999.00
Estimated Total Main. Cost	357.50	1356.50	1356.50	1356.50	1356.50
Present Value Factor	.90909	.8264463	.7513148	.6830135	.6209213
Present Value of Main. Cost (PV)	325.00	1121.07	1019.16	926.51	842.28

TABLE 4-7 (cont.)

Year of Analysis Period	6	7	8	9	10
Estimated Component Main. Cost	337.50	337.50	337.50	337.50	337.50
Estimated Chassis Main. Cost	20.00	20.00	20.00	20.00	20.00
Battery Replacement Cost	999.00	999.00	999.00	999.00	999.00
Estimated Total Main. Cost	1356.50	1356.50	1356.50	1356.50	1356.50
Present Value Factor	.5644739	.5131581	.4665074	.4240976	.3855433
Present Value of Main Cost (PV)	765.71	696.10	632.82	575.29	522.99

Present value of the fleet maintenance costs = $(\sum_{n=1}^{10} PV_n)\ 16 = (7426.93)16 =$ \$118,830.88

Where PM is the present value of the maintenance cost for an EV, AMC is the annual maintenance cost for an EV, and $\frac{1}{(1+i)^n}$ is the present value factor. The present value of the maintenance costs for an EV $7,426.93, was then multiplied by the number of vehicles in the EV fleet, 16, to determine the present value of the fleet maintenance costs. Through this process we calculated the present value of the fleet maintenance cost over the ten year analysis period to be $118,830.88 (Table 4-7).

To estimate the final element of the EV fleet life cycle cost, the vehicle salvage value, we contacted EV manufacturers and users to obtain the average salvage value of an EV after ten years. The salvage value of the EV fleet is made up of two elements. The first element involves the salvage value associated with the used batteries. Since batteries are included in the purchase price of the EV, at the end of the ten year period we would sell the EV with the batteries in it, and we must replace the battery pack yearly, we will have a battery pack to salvage in years 2 through 9 for each vehicle. The battery packs on the DJ-5E Electruck weigh approximately 1,300 pounds (9: 205), and these batteries are worth 8¢ per pound as scrap (41). Considering there are 16 vehicles, and one battery pack is worth $104.00 as scrap (Table 4-8), we will have a cash receipt of $1,664.00 in years 2 through 9 of the analysis period.

The second element of the fleet salvage value is the value associated with each EV at the end of the analysis period. Through interviews with manufacturers and users of EVs we have determined that an EV will be worth approximately 10 percent of its original purchase value at the end of ten years (41). By taking this value and multiplying it times 16 (the number of EVs in the fleet) we computed the salvage value of the EV fleet after ten years to be \$16,142.40 (Table 4-8).

Present value analysis was applied to these salvage figures to compute the present value of the salvage value associated with the EV fleet (Table 4-8). In equation form:

$$PS = \left(\sum_{n=2}^{9} (16B) \frac{1}{(1+i)^n} \right) + \left((1.6\ EV) \frac{1}{(1+i)} 10 \right)$$

Where PS is the present value of the salvage value associated with the EV fleet, B is the salvage value of a battery pack (104.00), and EV is the purchase price of an EV.

After completing the preceeding preliminary calculations we computed the life cycle cost of the EV fleet (Table 4-8). In equation form the fleet life cycle cost is:

$$LCC_{ev} = (P + PO + PM) - PS$$

Where LCC_{ev} is the life cycle cost of the EV fleet, P is the purchase price of the EV fleet, PO is the present value

TABLE 4-8

SALVAGE VALUE AND LIFE CYCLE COST OF THE EV FLEET

Salvage Value of an EV Fleet (in dollars)
Annual salvage value of battery packs = 1300 lbs @ 8¢ per lb = 104 x 16 vehicles = \$1664.00

Salvage value of vehicle fleet = \$1008.9 x 16 vehicles = \$16142.40

Year of Analysis Period	1	2	3	4	5
Salvage Value of Battery Packs	---	1664.00	1664.00	1664.00	1664.00
Salvage Value of Vehicles	---	---	---	---	---
Present Value Factor	.90909	.8264463	.7513148	.6830135	.6209213
Present Value of Salvage Revenues (PV)	---	1375.21	1250.19	1136.53	1033.21

TABLE 4-8 (cont.)

Year of Analysis Period	6	7	8	9	10
Salvage Value of Battery Packs	1664.00	1664.00	1664.00	1664.00	1664.00
Salvage Value of Vehicles	---	---	---	---	16142.40
Present Value Factor	.5644739	.5131581	.4665074	.4240976	.3855433
Present Value of Salvage Revenues (PV)	939.28	853.90	776.27	705.70	6223.59

Present value of fleet salvage revenues = $\sum_{n=1}^{10} PV_n$ = \$14,293.88

<u>Life Cycle Cost of the EV Fleet</u>

Life cycle cost = fleet purchase price + fleet maintenance cost + fleet operating cost - fleet salvage value

LCC = \$161,424.00 + \$118,830.88 + \$90,424.55 - \$14,293.88 = \$356,385.55

of the EV fleet operating costs over the ten year period, PM is the present value of the EV fleet maintenance costs over the ten year period, and PS is the present value of the salvage value associated with the EV fleet at the end of the ten year period. Through these calculations we arrived at a life cycle cost for the EV fleet of $356,385.55 (Table 4-8). When this figure is compared to the life cycle cost of the Internal Combustion Engine Pickup Fleet, $252,974.01 (Table 4-3), it is evident that the ICE pickup fleet is the low cost alternative for fleet replacement.

CHAPTER V

CONCLUSIONS AND RECOMMENDATIONS

This thesis discussed three basic concepts of economic analysis: the time value of money, life cycle cost, and reliability theory. Using these concepts, a method of economic analysis was developed to be used in evaluating the possible replacement of ICE vehicles with EVs. This methodology was demonstrated by evaluating two possible alternatives for replacement of the existing fleet of fifteen pickup trucks assigned to the 4950th Test Wing aircraft maintenance complex at Wright-Patterson AFB, Ohio. One alternative was to replace the existing pickup fleet with a fleet of fifteen new ICE pickup trucks. The other alternative was to replace the existing pickup fleet with a fleet of American Motors General DJ-5E Electruck EVs large enough to fulfill the same operational requirements as the current pickup fleet.

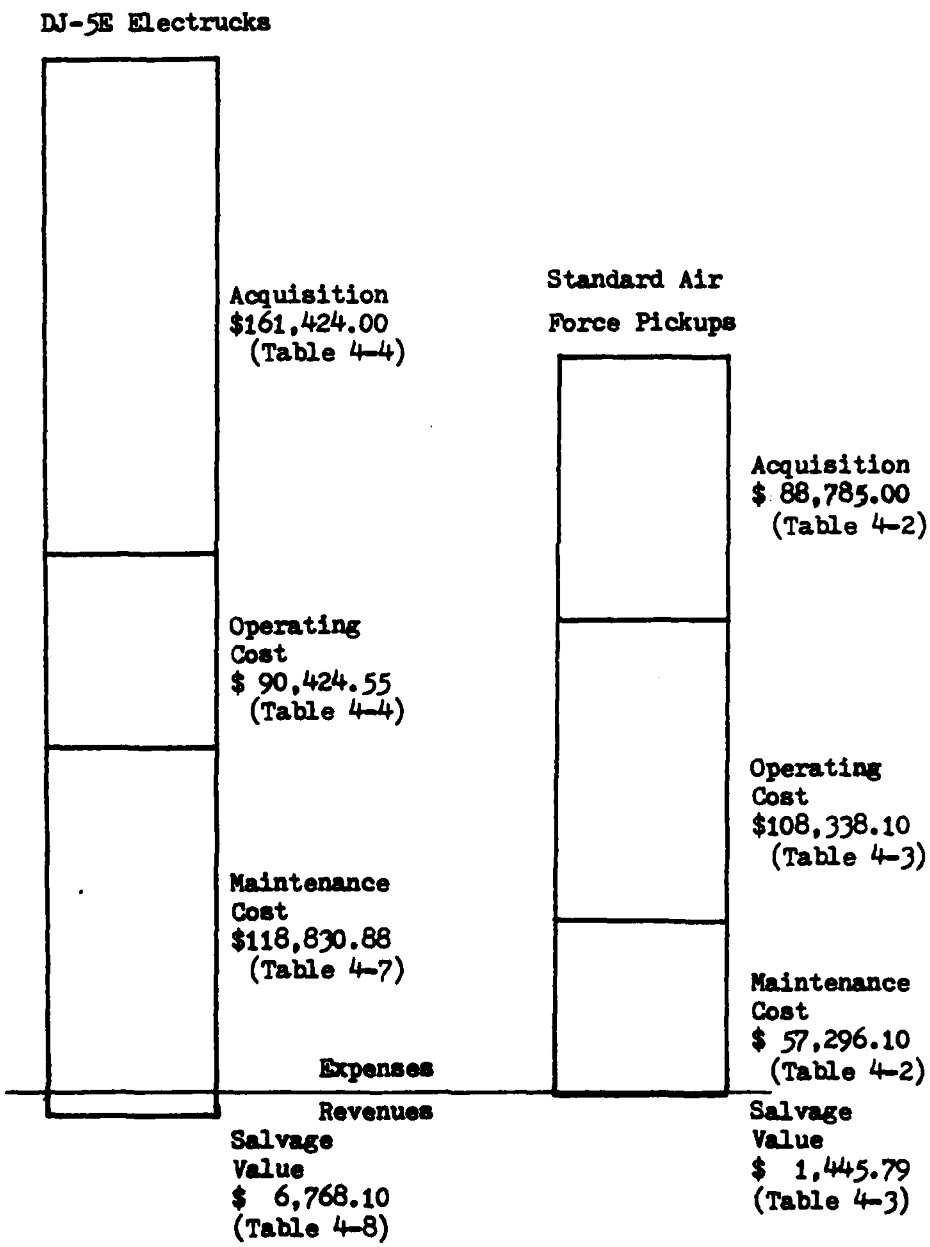
Through this research effort it was determined that sixteen American Motors General DJ-5E Electrucks would be required to provide the same level of service the fifteen ICE pickups are providing the 4950th Test Wing aircraft maintenance complex. An additional EV would be needed because EV range characteristically drops during cold weather

operation. Interviews with fleet operators indicated that EV range dropped from about 48 kilometers (30 miles) per discharge cycle to approximately 32 kilometers (20 miles) per discharge cycle during the winter months.

The ten year life cycle cost of the EV fleet was approximately $111,000 greater than the life cycle cost of the ICE pickup fleet ($363,911.33 versus $252,974.01). Figure 5-1 shows a comparative percentage breakdown of the present value in 1981 dollars of life cycle cost elements. These figures show that operating costs are only about 25 percent of the total life cycle costs of the EV fleet; acquisition and maintenance costs are the more significant cost elements. Life cycle cost of the pickup fleet was based on gasoline costing $0.30 per liter ($1.27 a gallon) (10) and an average fuel consumption rate of 3.07 kilometers per liter (8.1 miles per gallon). If the present pickup fleet remains in service and if all other life cycle cost elements remain constant, gasoline would have to increase to approximately $0.59 per liter ($2.50 a gallon) before the EV fleet would be a cost effective means of meeting the present service requirement. If more fuel efficient pickups were chosen to fill the present role of the standard Air Force pickups, the cost of fuel would have to rise further still.

Through the application of reliability theory, appropriate overhaul intervals for the battery pack, charger,

Figure 5.1. Comparative Breakdown of Life Cycle Cost Elements



controller, and motor were determined. The intervals were derived to ensure a minimum 80 percent aggregate reliability of the EV electric system in all operating intervals. Fleet managers may apply reliability theory to determine the aggregate reliability rate appropriate for them. The most significant factor affecting EV reliability and life cycle cost is battery pack reliability. Consequently, proper battery pack maintenance requires strong emphasis.

Present value analysis is a useful tool in developing life cycle cost models. This concept, when combined with data from EV fleet users, can be used to analyze EV life cycle costs. The model used is valid but greater EV cost data accuracy will be needed in the future as petroleum costs increase, making the EV alternative increasingly attractive.

This thesis did not explore the life cycle cost implications of replacing ICE pickups with more fuel efficient ICE pickups or augmenting the ICE pickup fleet with EVs of more moderate capability and price, as is being done in the Air Training Command experiment. The authors suggest exploration of both these alternatives as avenues for further research.

It was not possible to establish overhaul intervals, X_o, on the basis of standard deviations, σ, from the mean life, M, because σ and M were not contained in the data base compiled by the U.S. Postal Service. If they had been

included, this data could have been used to determine an appropriate overhaul interval with complete consideration of the wearout failure rate.

Motor pools are not geared for repair of EV electrical components. They will have to acquire electronics repair capability, obtain it from other logistics support functions or contract for repair of these items. Further research is needed to determine the most cost effective electronics repair concept. Managers of EV fleets presently in service must continue to carefully monitor all elements of EV life cycle cost and apply reliability theory in devising sound preventative maintenance programs.

Vehicle procurement personnel should continue to monitor EV technological progress for breakthroughs. They should consider contracting for repair of EV chargers and controllers with reliability improvement warranties. Under such a system the EV manufacturer would provide contract maintenance on these electric components and have a financial incentive for improving reliability of the equipment.

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